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DERIVATION OF THE INTERNATIONAL GEOMAGNETIC REFERENCE FIELD [IGRF(10/68)]

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16. Abstract

This report summarizes the results of the testing of the various magnetic field models against the available World Magnetic Survey data and describes the method by which the first International Geomagnetic Reference Field [IGRF(10/68)] was derived. The IGRF(10/68) was composed of contributions from the field models derived by Goddard Space Flight Center, Air Force Cambridge Research Laboratories, Royal Greenwich Observatory, Institute of Terrestrial Magnetism and Radiowave Propagation (IZMIRAN), and the U.S. Coast and Geodetic Survey.

IGRF(10/68) is a set of 80 internal, spherical harmonic coefficients and their first time derivatives, epoch 1965.0, referenced to a sphere of radius 6371.2 km. The rms residuals to surface and airborne magnetic-survey data taken between 1961 and 1965 average approximately 200γ. The rms deviations from selected Cosmos 49 (1964.7) and POGO (1965.8-1967.9) satellite observations of total field range from 30γ to 60γ.

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INTRODUCTION

This paper summarizes some of the computations that were made at the International Association of Geomagnetism and Aeronomy (IAGA) Symposium in Washington, D. C., October 22-25, 1968, that led to the resolution by the Working Group on the Analysis of the Geomagnetic Field (Reporter, A. J. Zmuda) to propose an International Geomagnetic Reference Field (IGRF). The basic requirements established by Dr. Zmuda following the discussion at previous meetings called for the IGRF to consist of no more than 80 spherical harmonic coefficients of internal origin, epoch 1965.0, each being tabulated together with its first time derivative. These coefficients were to represent true spherical harmonics describing the field, not "quasi-spherical" harmonics resulting from derivations neglecting the oblateness of the earth. Further, only sets of coefficients submitted to the Working Group on or prior to March 15, 1968, were to be considered.

These sets of spherical harmonic coefficients are given in Table 1. They are each updated to 1965.0 and are limited to an n^* (maximum degree n and order m of the spherical harmonic coefficients) of eight. Of the sets given, all except those in Tables 1(g) and 1(h) take into account the oblateness of the earth in their derivation. Most of the field descriptions appear in the World Magnetic Survey (WMS) Volume (Zmuda, 1971). However, a few have also been published separately, as follows.

Table	Field Model	Reference
1(a)	GSFC(12/66)	Cain et al., 1967
1(g)	USC&GS[1]	Hurwitz et al., 1966
1(h)	RGO-1 (LME)[2]	Leaton et al., 1965

[1]United States Coast & Geodetic Survey.

[2]Royal Greenwich Observatory (RGO) model 1, based on Leaton, Malin, and Evans (1965).

Table 1--Spherical harmonic coefficients and their derivatives.

EPOCH = 1965.0 GSFC(12/66) SET 1

n	m	g	h	$\dot{g}$	$\dot{h}$
1	0	-30333	0	13.7	0.0
1	1	-2117	5759	9.3	-3.9
2	0	-1660	0	-24.1	0.0
2	1	2997	-2002	-0.2	-14.0
2	2	1561	119	-5.8	-16.7
3	0	1299	0	-1.5	0.0
3	1	-2043	-397	-10.8	5.7
3	2	1289	240	2.4	2.5
3	3	847	-167	-6.8	-6.6
4	0	957	0	1.5	0.0
4	1	807	149	0.7	-2.2
4	2	495	-274	-1.7	0.1
4	3	-394	11	0.7	1.7
4	4	249	-280	-3.5	-6.8
5	0	-224	0	1.8	0.0
5	1	359	15	0.6	2.0
5	2	247	126	3.7	1.6
5	3	-29	-128	-0.0	-2.6
5	4	-161	-106	-0.5	0.5
5	5	-52	81	2.0	-0.2
6	0	47	0	-0.4	0.0
6	1	62	-11	0.9	0.1
6	2	4	105	0.9	0.0
6	3	-225	70	2.6	2.6
6	4	2	-30	0.8	-1.3
6	5	-1	-12	0.1	0.5
6	6	-107	-9	0.3	0.8
7	0	69	0	-0.6	0.0
7	1	-56	-59	-0.4	-1.0
7	2	0	-27	-1.6	0.1
7	3	11	-6	-0.9	0.5
7	4	-24	11	0.0	0.8
7	5	-7	22	-0.7	-0.4
7	6	15	-20	-0.2	0.6
7	7	0	-17	-0.7	1.0
8	0	10	0	0.4	0.0
8	1	9	3	0.5	-0.6
8	2	0	-13	1.9	-0.3
8	3	-10	4	-0.1	0.1
8	4	-4	-20	0.4	-0.8
8	5	5	5	-0.1	0.0
8	6	-6	22	0.5	0.1
8	7	12	-3	-0.2	-0.4
8	8	5	-19	-0.5	-0.4

TABLE 1(a)

EPOCH = 1965.0 AFCRL(3/68)

n	m	g	h	$\dot{g}$	$\dot{h}$
1	0	-30339	0	12.0	0.0
1	1	-2133	5774	6.7	-0.9
2	0	-1657	0	-27.6	0.0
2	1	2993	-2016	-0.2	-15.9
2	2	1579	140	-3.6	-15.4
3	0	1302	0	0.3	0.0
3	1	-2039	-409	-10.2	5.0
3	2	1290	239	1.2	2.1
3	3	855	-195	-6.8	-10.9
4	0	965	0	0.7	0.0
4	1	807	142	0.8	-1.4
4	2	495	-286	-0.3	-1.4
4	3	-391	1	-0.5	2.6
4	4	269	-269	-1.0	-4.4
5	0	-220	0	3.3	0.0
5	1	351	26	0.6	2.2
5	2	239	129	2.6	2.3
5	3	-26	-118	0.4	-1.8
5	4	-151	-117	1.6	-1.8
5	5	-44	80	4.0	-0.1
6	0	47	0	-1.2	0.0
6	1	56	-16	-1.0	-0.5
6	2	7	104	0.5	0.1
6	3	-237	68	1.1	1.9
6	4	1	-27	0.4	0.2
6	5	-12	-8	-2.7	0.6
6	6	-103	-17	0.4	-0.4
7	0	75	0	0.2	0.0
7	1	-53	-52	-0.3	-0.6
7	2	-3	-30	-1.0	-0.8
7	3	20	-10	0.8	0.9
7	4	-27	4	-0.5	-0.4
7	5	-11	20	-0.8	-0.4
7	6	6	-16	0.7	1.7
7	7	-12	-15	-2.2	1.3
8	0	9	0	-0.2	0.0
8	1	5	10	0.3	-0.3
8	2	-5	-14	0.0	-0.2
8	3	-15	13	-0.7	-1.0
8	4	-8	-15	-0.9	-0.4
8	5	3	2	-0.2	-0.4
8	6	-7	19	-0.4	-0.2
8	7	9	-4	-1.7	-1.3
8	8	8	-13	-0.9	-0.7

TABLE 1(b)

EPOCH = 1965.0 RGO(3/68)-2 (MALIN)

n	m	g	h	$\dot{g}$	$\dot{h}$
1	0	-30350	0	17.0	0.0
1	1	-2115	5770	9.0	0.0
2	0	-1640	0	-24.0	0.0
2	1	2979	-2000	-1.0	-12.0
2	2	1585	115	2.0	-18.0
3	0	1279	0	0.0	0.0
3	1	-2008	-425	-10.0	5.0
3	2	1289	241	-1.0	1.0
3	3	862	-156	-1.0	-9.0
4	0	940	0	-1.0	0.0
4	1	792	161	0.0	1.0
4	2	484	-280	-4.0	1.0
4	3	-389	11	1.0	3.0
4	4	259	-254	-3.0	-3.0
5	0	-207	0	1.0	0.0
5	1	367	18	0.0	2.0
5	2	239	133	3.0	2.0
5	3	-28	-122	-1.0	-2.0
5	4	-166	-97	-1.0	1.0
5	5	-64	75	1.0	0.0
6	0	39	0	0.0	0.0
6	1	55	-17	0.0	-2.0
6	2	2	107	1.0	1.0
6	3	-233	58	2.0	2.0
6	4	7	-31	0.0	-1.0
6	5	3	-16	0.0	0.0
6	6	-112	-10	-1.0	1.0
7	0	77	0	0.0	0.0
7	1	-47	-46	0.0	0.0
7	2	2	-25	0.0	0.0
7	3	12	-10	0.0	0.0
7	4	-28	8	0.0	0.0
7	5	-12	24	0.0	0.0
7	6	15	-22	0.0	0.0
7	7	5	-21	0.0	0.0
8	0	6	0	0.0	0.0
8	1	13	-4	0.0	0.0
8	2	-6	-7	0.0	0.0
8	3	-17	1	0.0	0.0
8	4	2	-16	0.0	0.0
8	5	10	5	0.0	0.0
8	6	-5	24	0.0	0.0
8	7	12	4	0.0	0.0
8	8	6	-15	0.0	0.0

TABLE 1(c)

EPOCH = 1965.0 IZMIRAN(3/68)

n	m	g	h	$\dot{g}$	$\dot{h}$
1	0	-30358	0	18.6	0.0
1	1	-2147	5706	7.7	-2.5
2	0	-1630	0	-25.1	0.0
2	1	3000	-2015	0.1	-9.8
2	2	1552	201	-1.2	-15.8
3	0	1297	0	0.8	0.0
3	1	-2035	-391	-8.9	4.3
3	2	1289	264	0.0	0.7
3	3	758	-229	-1.7	-5.6
4	0	976	0	0.2	0.0
4	1	814	138	0.3	1.4
4	2	486	-308	-2.3	0.9
4	3	-388	-1	0.0	2.5
4	4	266	-174	-1.3	-1.6
5	0	-242	0	0.6	0.0
5	1	344	-6	0.3	0.4
5	2	262	102	1.1	1.4
5	3	-5	-99	-0.4	-1.2
5	4	-174	-106	-0.7	0.2
5	5	-42	52	0.1	0.2
6	0	62	0	-0.5	0.0
6	1	68	-18	0.3	-0.4
6	2	6	112	0.7	0.2
6	3	-226	76	1.3	0.9
6	4	2	-58	0.4	0.0
6	5	-20	5	0.0	0.0
6	6	-160	-30	0.0	0.0
7	0	64	0	0.0	0.0
7	1	-55	-73	0.0	0.0
7	2	4	-27	0.0	0.0
7	3	3	-14	0.0	0.0
7	4	-19	12	0.0	0.0
7	5	-8	31	0.0	0.0
7	6	13	-16	0.0	0.0
7	7	-10	-13	0.0	0.0
8	0	16	0	0.0	0.0
8	1	10	4	0.0	0.0
8	2	-9	-22	0.0	0.0
8	3	-10	2	0.0	0.0
8	4	-6	-11	0.0	0.0
8	5	18	-2	0.0	0.0
8	6	8	26	0.0	0.0
8	7	16	-10	0.0	0.0
8	8	8	-8	0.0	0.0

TABLE 1(d)

EPOCH = 1965.0 POGO(3/68)

n	m	g	h	$\dot{g}$	$\dot{h}$
1	0	-30338	0	26.2	0.0
1	1	-2112	5770	4.7	-6.1
2	0	-1661	0	-23.3	0.0
2	1	2999	-2011	2.3	-9.0
2	2	1595	123	11.8	-8.8
3	0	1302	0	-8.2	0.0
3	1	-2043	-406	-9.3	10.7
3	2	1299	239	-0.8	2.6
3	3	856	-160	-11.0	0.8
4	0	955	0	-0.3	0.0
4	1	803	152	-1.5	4.3
4	2	478	-275	-6.0	-0.8
4	3	-382	15	-6.3	2.9
4	4	254	-230	-3.3	-14.2
5	0	-222	0	3.8	0.0
5	1	361	19	-0.5	-1.0
5	2	247	127	1.2	1.1
5	3	-33	-126	1.8	-4.5
5	4	-168	-98	-3.5	0.7
5	5	-54	76	1.2	-5.3
6	0	46	0	-0.3	0.0
6	1	62	-11	0.9	-1.0
6	2	11	106	2.1	-0.5
6	3	-233	68	5.7	0.5
6	4	3	-45	0.6	2.0
6	5	-12	3	2.1	0.8
6	6	-144	-25	-3.9	0.1
7	0	72	0	-0.9	0.0
7	1	-53	-63	0.0	-0.5
7	2	3	-27	0.1	0.8
7	3	14	-8	-0.8	0.5
7	4	-22	7	2.5	1.2
7	5	-6	24	0.4	1.2
7	6	12	-19	0.2	-0.6
7	7	-10	-19	1.4	1.9
8	0	10	0	0.4	0.0
8	1	3	10	0.4	0.4
8	2	-4	-13	0.5	-0.2
8	3	-10	8	-1.5	-0.5
8	4	-5	-13	-0.6	-1.6
8	5	14	-1	-0.7	0.0
8	6	5	26	1.5	0.1
8	7	15	-10	0.4	-0.1
8	8	9	-11	-2.6	1.1

TABLE 1(e)

EPOCH = 1965.0 AFCRL(11/67)

n	m	g	h	$\dot{g}$	$\dot{h}$
1	0	-30332	0	12.4	0.0
1	1	-2137	5791	6.3	0.0
2	0	-1658	0	-27.5	0.0
2	1	2992	-2002	-0.3	-13.8
2	2	1573	142	-3.0	-13.9
3	0	1306	0	0.3	0.0
3	1	-2035	-404	-9.7	4.0
3	2	1294	250	1.4	3.3
3	3	866	-184	-4.5	-12.0
4	0	954	0	-0.3	0.0
4	1	812	139	0.9	-1.9
4	2	491	-288	0.4	-2.1
4	3	-384	6	-0.9	3.4
4	4	275	-272	-0.4	-3.2
5	0	-229	0	2.5	0.0
5	1	354	17	1.1	1.4
5	2	241	120	2.5	0.5
5	3	-28	-129	0.4	-3.0
5	4	-144	-110	3.1	-1.9
5	5	-53	71	4.5	-0.3
6	0	46	0	-1.6	0.0
6	1	59	-5	-1.3	1.7
6	2	7	109	-0.3	1.5
6	3	-244	68	0.9	1.5
6	4	-6	-35	-0.5	-0.6
6	5	-1	-14	-2.1	-0.5
6	6	-92	-17	1.5	-0.9
7	0	76	0	1.1	0.0
7	1	-52	-57	-0.0	-1.1
7	2	-2	-25	-1.0	-0.9
7	3	19	-15	-1.1	0.5
7	4	-32	5	-1.1	-1.0
7	5	-19	20	-1.5	-0.5
7	6	10	-24	1.0	1.5
7	7	-7	-22	-2.3	0.9
8	0	14	0	-0.4	0.0
8	1	7	9	0.6	0.2
8	2	-5	-6	0.3	0.8
8	3	-16	18	-0.2	-0.5
8	4	-2	-22	-0.6	-0.0
8	5	2	5	-0.7	-1.1
8	6	-3	16	-0.5	-1.5
8	7	2	-7	-1.9	-1.9
8	8	0	-25	-0.7	-3.4

TABLE 1(f)

EPOCH = 1965.0 USCGS(5/66&3/68)

n	m	g	h	$\dot{g}$	$\dot{h}$
1	0	-30388	0	15.0	0.0
1	1	-2117	5760	10.5	-4.0
2	0	-1637	0	-21.1	0.0
2	1	2981	-2004	2.7	-7.1
2	2	1583	127	0.5	-17.8
3	0	1153	0	1.3	0.0
3	1	-1989	-425	-14.1	1.1
3	2	1282	243	0.9	-3.0
3	3	855	-161	-2.5	-6.2
4	0	925	0	-4.8	0.0
4	1	806	148	-0.8	0.9
4	2	489	-293	-6.6	7.3
4	3	-382	11	-1.8	4.6
4	4	256	-249	-1.8	-5.0
5	0	-203	0	2.6	0.0
5	1	348	10	4.0	4.9
5	2	242	135	3.8	1.4
5	3	-31	-122	3.8	-4.3
5	4	-158	-95	0.8	4.2
5	5	-66	76	-0.8	-1.4
6	0	58	0	1.7	0.0
6	1	71	-16	-1.6	-1.9
6	2	1	108	2.3	-3.3
6	3	-232	55	2.3	2.8
6	4	-3	-23	-3.8	-3.2
6	5	1	-13	0.5	-0.6
6	6	-108	-13	-0.8	3.2
7	0	76	0	-2.1	0.0
7	1	-33	-36	-0.9	-3.8
7	2	4	-14	-0.9	2.2
7	3	14	-10	-2.4	0.6
7	4	-25	8	1.8	0.6
7	5	-14	25	1.4	2.8
7	6	20	-24	-1.5	-1.2
7	7	6	-18	-0.1	-0.9
8	0	3	0	0.4	0.0
8	1	12	-11	1.2	1.4
8	2	-3	-6	0.9	-0.4
8	3	-21	-3	1.1	-0.7
8	4	0	-15	0.2	0.3
8	5	3	2	-0.1	-1.3
8	6	-8	20	1.4	-1.9
8	7	14	0	0.3	0.2
8	8	8	-16	-1.1	-0.2

TABLE 1(g)

EPOCH = 1965.0 RGO(3/68)-1(LEATON,BASED ON LME)

n	m	g	h	$\dot{g}$	$\dot{h}$
1	0	-30372	0	15.5	0.0
1	1	-2083	5781	8.3	0.6
2	0	-1635	0	-26.6	0.0
2	1	2949	-1993	-1.3	-11.4
2	2	1582	108	1.3	-18.2
3	0	1161	0	0.0	0.0
3	1	-2025	-405	-9.5	3.2
3	2	1291	238	-1.9	1.6
3	3	872	-148	-0.6	-8.5
4	0	930	0	0.6	0.0
4	1	809	153	1.0	3.9
4	2	489	-274	-2.2	-0.7
4	3	-395	8	0.2	2.7
4	4	262	-257	-3.0	-2.7
5	0	-179	0	0.8	0.0
5	1	360	21	0.4	1.9
5	2	249	135	1.6	2.3
5	3	-13	-121	-0.3	-1.8
5	4	-174	-100	-1.1	1.4
5	5	-63	74	1.7	0.5
6	0	39	0	0.0	0.0
6	1	56	-18	-0.5	-2.2
6	2	11	102	1.8	0.2
6	3	-244	59	1.4	0.9
6	4	21	-38	0.6	-2.1
6	5	8	-21	0.2	-0.1
6	6	-116	-9	-2.2	-0.2
7	0	81	0	0.0	0.0
7	1	-54	-48	0.0	0.0
7	2	7	-32	0.0	0.0
7	3	10	-14	0.0	0.0
7	4	-36	6	0.0	0.0
7	5	-15	24	0.0	0.0
7	6	11	-21	0.0	0.0
7	7	4	-24	0.0	0.0
8	0	8	0	0.0	0.0
8	1	18	2	0.0	0.0
8	2	-8	-5	0.0	0.0
8	3	-20	7	0.0	0.0
8	4	6	-18	0.0	0.0
8	5	19	9	0.0	0.0
8	6	-3	27	0.0	0.0
8	7	10	10	0.0	0.0
8	8	4	-14	0.0	0.0

TABLE 1(h)

TEST DATA

Although no explicit formula was agreed upon prior to the meeting for the derivation of an IGRF, there was an understanding that the model had to correspond to the available survey data.

Since the epoch of this IGRF was 1965, data were arbitrarily cut off at 1961, a year chosen so the results would not be too heavily weighted by observations prior to 1965. Testing was done on all data available since that date. These were divided into the major categories below.

(1) Observatory annual means of surface magnetic fields, 1961-1967.

(2) Surface magnetic surveys. This category includes land surveys, repeat stations, shipboard and ship-towed observations.

(3) Aeromagnetic survey of Japan, 1965 (Nagata, 1966).

(4) Aeromagnetic survey of Canada, 1961-1963.

(5) Aeromagnetic survey of Scandinavia, 1965 (Eleman et al., 1969).

(6) Project MAGNET worldwide (principally oceanic) airborne survey, 1961-1966 (USNOO, 1965).

(7) OGO 2 data, as available during magnetically quiet intervals, October 1965 to September 1967.

(8) OGO 4 data during magnetically quiet intervals from July to December 1967.

(9) 1964-83c observations, 1964-1965 (Zmuda et al., 1968).

(10) Cosmos 49 observations, 1964.8 (Dolginov et al., 1967).

(11) Other airborne (towed proton-magnetometer) data.

All of the nonsatellite data were obtained from the file prepared by the Geomagnetic Division of the U.S. Coast and Geodetic Survey (E. Fabiano and S. Cain, WMS Volume). This file contained the contributions from many separate organizations and survey groups and is constantly updated as new observations are submitted. This file was edited by rejecting those observations deviating by more than 1000γ from the GSFC(12/66) model (using $n^* = 10$). This procedure was used to eliminate the highly anomalous data beyond about five times the root-mean-square (rms) deviation. Since all models were truncated to $n^* = 8$ for testing, no particular advantage was given to GSFC(12/66). This model was used since it fitted the data set best; hence, it requires the least elimination of data. The amount rejected was small, as seen in Table 2.

The OGO 2 and OGO 4 data (sampled every 30 seconds or at a spacing of approximately 200 km) were initially selected from periods of time for which $K_p = 0$. They were then fit with a special model listed in Table 3(a) [POGO(10/68)] employing 143 internal coefficients and their first time derivatives. The distribution of deviations of the data from this fit was as follows.

$\|\Delta F\| \gamma$	0		10		20		30		40		50		60		70		100		200		600	Total
Obs.		27,646		4218		589		141		23		26		6		2		9		4		32,664

Since the distribution indicated that they were probably anomalous, the 15 observations over 70γ were rejected and the resulting rms deviation computed to be 7γ. The remaining 32,649 observations were included in the testing.

The Cosmos 49 data were similarly treated by fitting with a special function and eliminating those data that deviated significantly from the rest. The data were prepared by the U.S. Coast and Geodetic Survey from the catalog (Dolginov et al., 1967) published by the Institute of Terrestrial Magnetism and Radiowave Propagation (IZMIRAN). These were sorted into time order and each fourth observation fit with a series of 99 spherical harmonic coefficients by a model labelled COSMOS(9/68), listed in Table 3(b). Data deviating more than 100γ from the fitting surface were rejected in the coefficient determination. The distribution of residuals from this model, COSMOS(9/68), is as follows.

$\|\Delta F\| \gamma$	0		10		20		30		40		50		60		70		80		90		100		Total
Obs.		1853		1243		648		271		93		41		23		18		19		15		138	4362

The use of every fourth observation in the fit is adequate since each orbit then contains about 10 observations for the shortest wavelength of the fitting function used ($n^* = 9$ corresponds to $360°/9 = 40°$). Since the rms deviation of these data from the COSMOS(9/68) field was 21γ, the selection used for model testing consisted of those deviating by less than 60γ, a total of 16,554 observations from the approximately 18,000 originally available.

The 1964-83c observations entered the testing unedited except for the rejection of one spurious point that gave a $|\Delta F| > 1000\gamma$.

Table 2—Nonsatellite data eliminated for $\Delta C > 1000\gamma$.

Data Type	Component Observations*	Data Rejected	
		Number	Percent
(1) Observatory	1984	34	1.7
(2) Surface	22,425	204	.9
(3) Japanese Air	1461	6	.4
(4) Canadian Air	9470	27	.3
(5) Scandinavian Air	6973	1	.01
(6) Project MAGNET	104,228	401	.4
(7) Other Air	1763	9	.5

*In this and ensuing discussion a value of D, I, H, Z, or F is counted as one observation even though other values may have been measured at the same time and location.

Table 3(a)—POGO(10/68) spherical harmonic coefficients and their time derivatives (Epoch 1960.0).

n	m	g	h	$\dot{g}$	$\dot{h}$
1	0	-30465.0		25.42	
1	1	-2163.3	5791.0	9.88	-4.66
2	0	-1541.4		-23.90	
2	1	2976.3	-1977.2	3.50	-7.07
2	2	1607.5	156.6	-2.14	-10.70
3	0	1325.8		-5.59	
3	1	-1983.7	-445.3	-11.52	8.48
3	2	1316.9	233.4	-4.41	0.68
3	3	842.0	-94.9	2.87	-14.89
4	0	959.1		-0.62	
4	1	819.6	135.4	-2.51	3.45
4	2	486.4	-266.7	-1.22	-0.39
4	3	-372.4	20.7	-2.96	-0.87
4	4	256.2	-241.5	0.86	-6.52
5	0	-234.3		2.72	
5	1	357.7	16.9	0.48	0.05
5	2	233.9	113.3	3.17	3.00
5	3	-21.0	-128.7	-2.46	0.32
5	4	-147.1	-115.1	-0.89	3.11
5	5	-45.2	130.3	-3.15	-6.35
6	0	49.1		-0.61	
6	1	54.5	-9.6	1.06	-0.26
6	2	4.8	106.4	0.62	-0.48
6	3	-249.1	56.8	3.95	2.58
6	4	1.7	-27.2	-0.94	-0.80
6	5	-3.7	-14.9	1.49	0.50
6	6	-91.6	-4.3	-1.67	0.82
7	0	75.9		-0.89	
7	1	-52.4	-57.9	-0.21	-0.87
7	2	8.0	-25.0	-1.08	-0.46
7	3	10.0	-0.8	0.70	-1.02
7	4	-36.7	6.3	1.07	0.25
7	5	-8.3	9.5	0.96	1.88
7	6	6.6	-11.7	1.01	-2.43
7	7	-22.7	-37.6	5.23	2.32
8	0	7.4		0.61	
8	1	6.0	10.1	-0.12	-0.15
8	2	-8.1	-13.0	0.87	-0.10
8	3	-9.2	11.5	-0.33	-1.22
8	4	-0.8	-16.4	-0.14	-0.26
8	5	9.1	5.5	-0.85	0.15
8	6	-11.4	22.3	0.99	-0.37
8	7	7.9	-4.9	0.81	0.29
8	8	35.1	-26.2	-4.98	0.91
9	0	11.0		-0.24	
9	1	6.6	-20.4	0.30	-0.38
9	2	1.8	14.4	0.04	0.16
9	3	-12.5	0.6	0.04	0.67
9	4	15.8	-1.5	-0.40	-0.14
9	5	1.7	1.4	-0.28	-0.83
9	6	2.6	3.4	-0.57	1.30
9	7	8.7	14.8	-1.32	-0.33
9	8	5.1	2.4	-0.14	-0.38
9	9	-2.4	-0.9	0.50	0.99
10	0	-2.6		-0.01	
10	1	-2.0	1.1	-0.09	0.21
10	2	1.0	0.9	0.12	0.05
10	3	-5.5	-0.3	0.19	0.54
10	4	-0.7	7.5	-0.20	-0.26
10	5	7.5	-2.3	-0.02	-0.30
10	6	7.8	1.4	-0.43	-0.03
10	7	1.7	-0.5	-0.33	-0.39
10	8	-5.3	4.3	1.03	-0.02
10	9	1.3	8.0	0.22	-1.04
10	10	-2.7	-13.7	0.46	0.79
11	0	2.3		0.03	
11	1	-1.8	-0.8	0.11	0.35
11	2	-2.1	4.4	0.05	-0.26
11	3	5.5	-0.1	-0.30	-0.17
11	4	-1.5	-3.9	0.01	0.17
11	5	2.4	-0.6	-0.34	0.18
11	6	-3.5	1.8	0.48	-0.50
11	7	-1.3	-3.2	0.52	0.23
11	8	2.5	0.8	-0.19	-0.34
11	9	-1.2	-5.9	-0.03	0.37
11	10	12.7	-1.7	-1.65	0.22
11	11	5.0	10.5	-0.40	-1.55

$$g(t) = g + \dot{g}(t - 1960)$$
$$h(t) = h + \dot{h}(t - 1960)$$

TEST RESULTS

The various models were tested against the data sets both with the limitation of 80 coefficients and also using all coefficients if more were available. Table 4(a) illustrates for the GSFC(12/66) model the distribution of residuals using the first 80 coefficients as well as the full number. Since the surface data were edited with this model using a 1000γ criterion, there can be no residuals above this figure with 120 coefficients. The effect of the truncation is to increase the rms residuals by 10γ-20γ independent of their magnitude. Using 80 terms has only a small percentage effect on the surface data since magnetic anomalies account for a great deal of the scatter. The consequences for the satellite data are more obvious as seen in the OGO 2 results. Here the effect is to increase the number of residuals in the 50γ-100γ range from 5 to 10 percent of the total data, and to push the number over 100γ from 1 to 3 percent.

Table 3(b)—COSMOS(9/68) spherical harmonic coefficients.

n	*m*	*g*	*h*	*n*	*m*	*g*	*h*
1	0	-30415.2		7	0	30.3	
1	1	-2143.1	5721.6	7	1	-52.4	-70.2
2	0	-1640.5		7	2	4.5	-28.2
2	1	3001.9	-2014.4	7	3	5.4	-14.2
2	2	1556.8	189.2	7	4	-20.3	13.3
3	0	1211.1		7	5	-9.1	29.6
3	1	-2033.8	-388.6	7	6	11.8	-15.6
3	2	1286.4	258.0	7	7	-12.1	-15.4
3	3	780.0	-233.8	8	0	15.5	
4	0	969.6		8	1	11.1	3.8
4	1	816.3	137.6	8	2	-8.5	-21.1
4	2	487.2	-301.9	8	3	-9.3	2.2
4	3	-386.7	0.5	8	4	-6.8	-12.2
4	4	253.6	-186.4	8	5	17.0	-1.6
5	0	-299.4		8	6	7.7	27.1
5	1	348.5	-0.5	8	7	16.6	-9.3
5	2	264.3	106.7	8	8	7.9	-6.5
5	3	-12.4	-98.3	9	0	-9.1	
5	4	-172.3	-108.3	9	1	7.2	-29.3
5	5	-35.5	57.0	9	2	11.0	5.6
6	0	57.6		9	3	-14.6	13.5
6	1	69.2	-19.1	9	4	9.5	-2.3
6	2	5.9	110.4	9	5	2.5	-5.1
6	3	-228.1	74.9	9	6	0.7	6.4
6	4	6.4	-56.0	9	7	3.9	9.6
6	5	-19.4	3.3	9	8	3.3	-1.7
6	6	-158.9	-33.8	9	9	-2.3	0.5

These distributions were also calculated for each of the other test models, and the rms values compiled in Table 4(b). Here the correspondence of each data set to a model can be readily observed.

Although for each model there is an improvement with an increase in the number of coefficients, the difference is generally smaller for those groups of observations with higher average residuals.

WEIGHTING OF IGRF

It was decided that a weighted average of coefficients would provide the best compromise for an IGRF. Due to the restriction that models to be included should be based on truly spherical coefficients, the RGO(LME) and USC&GS models were eliminated from the main field averaging. Since the surface-data residuals were so greatly influenced by crustal anomalies, it was decided to base these weights on the residuals to the satellite data.

Several different weighting schemes were tried. Generally, the precise choice of weights used did not alter the overall results appreciably as long as those models best fitting the satellite data were given preference. The POGO(3/68) and AFCRL(11/67) models were eliminated from the considerations since each organization submitted another model.

After the presentation of several semiqualitative arguments that the IGRF would be most useful circa 1965.0, the following tabulation of relative weights was agreed upon. Each weight was applied as an inverse square factor in combining the main field terms.

Model	σ (weight, in γ)
GSFC(12/66)	40
AFCRL(3/68)	70
RGO(3/68)-2	80
IZMIRAN(3/68)	100

The GSFC model was given the 40γ weight (even though it had a 61γ residual to the OGO 4 data) because the OGO 2 figure was 39γ, the other satellite residuals were low, and it has the overall lowest residuals to the surface data. The AFCRL model and RGO contributions were roughly equivalent but the AFCRL was given a slightly smaller weight because of its lower residual to OGO 2, Cosmos 49, and the surface data. The IZMIRAN model was assigned a slightly higher weight because of its uncertainty in the polar regions, the model being derived from data at less than 50° latitude. This decision is supported by the model's relatively high residuals to data sets containing polar contributions (e.g., OGO 2, OGO 4, observatory, land/sea, Scandinavian airborne, and Project MAGNET).

There was less basis for rational comparisons in combining the secular change terms. Hence each model previously used was weighted equally, and the USC&GS and RGO-1 models were included since the secular change was independently derived for each.

Although more lengthy considerations may have resulted in an improved procedure for deriving the first IGRF, this formulation provided a model composed of some contribution from each organization. At the same time, within the restrictions on the number of coefficients, it produced a model which agrees tolerably well with the test data set. This agreement is seen in the last column of Table 4. Surprisingly, the procedure appeared to produce a residual equal to or less than that of the contributing models for some of the data sets at the $n^* = 8$ truncation level.

THE RESULTING MODEL IGRF(10/68)

Since the IGRF is a composite of several models, it can be compared with each, as in Table 5. Here is listed for each of the contributing coefficient sets the deviation from the resulting IGRF. Although the disagreements between the various terms are sometimes relatively large for those with amplitudes of the order of 1γ to 10γ, those of higher magnitude are surprisingly close to one another. Of the main field terms, the largest discrepancy seems to be among those having $m = n$.

The final IGRF(10/68) coefficients are given in Table 6. Maps of the field and its secular change are given in Appendix 1. Appendix 2 gives a possible minor modification based on a suggested change of scale to a standard mean earth radius of 6371 in place of 6371.2 km.

OBSERVATIONS AND RECOMMENDATIONS

It is appropriate at this point to make some observations on the domain of applicability of the international reference field and on its deficiencies and limitations. As can be seen in this report

Table 4(a)—Distribution of residuals from GSFC(12/66) using $n^* = 8$ (80 coefficients) and $n^* = 10$ (120 coefficients).

Data Type	Number of Coefficients	Residual Range (γ)						Total Number of Observations	rms (γ)
		0	50	100	250	500	1000		
Observatory	120	740	414	532	205	59	0	1950	187
	80	490	499	653	227	81	0		198
Land/Sea	120	7089	5418	7071	2081	562	0	22,221	180
	80	5202	4686	8778	2876	660	19		202
Japanese Air	120	362	301	491	252	49	0	1455	211
	80	331	274	504	294	51	1		226
Canadian Air	120	2112	1935	3633	1516	247	0	9443	202
	80	1865	1683	3593	1974	328	0		225
Scandinavian Air	120	2113	1718	2573	537	31	0	6972	145
	80	1715	1560	2889	776	32	0		162
Project MAGNET	120	28,130	23,357	37,245	13,003	2101	0	103,827	186
	80	23,967	21,834	39,609	15,987	2397	33		200
Cosmos 49	120	15,446	1095	13	0	0	0	16,554	27
	80	11,557	4463	534	0	0	0		48
1964-83c	120	1242	75	13	0	0	0	1330	28
	80	1206	112	12	0	0	0		32
OGO 2	120	18,296	948	249	0	0	0	19,493	27
	80	16,878	2022	592	1	0	0		39
OGO 4	120	9300	3037	819	0	0	0	13,156	51
	80	8448	3363	1341	2	0	0		61

Table 4(b)—Root-mean-square deviations of test data from various models using $n^* = 8$ and n^* = maximum degree and order of expansions.

Data Type	Data	n^*	GSFC 12/66	POGO 3/68	POGO 10/68	AFCRL 11/67	AFCRL 3/68	RGO-1(LME)	RGO-2(Malin)	IZMIRAN	USC&GS	IGRF 10/68
Observatory	1950	8	198	211	203	208	208	223	202	272	245	196
		max	187	204	193	201	197			271	236	
Land/Sea	22,221	8	202	203	207	214	204	290	253	258	331	201
		max	180	186	187	209	192			248	323	
Japanese Air	1455	8	226	234	239	223	243	249	255	259	276	227
		max	211	215	220	216	221			244	233	
Canadian Air	9443	8	225	227	226	240	238	230	223	234	249	223
		max	202	209	205	212	221			237	236	
Scandinavian Air	6972	8	162	159	159	163	178	185	162	255	197	167
		max	145	138	140	150	164			253	190	
Project MAGNET	103,827	8	200	232	215	216	209	234	216	330	244	201
		max	186	221	202	217	204			325	237	
Cosmos 49	16,554	8	48	49	51	80	67	149	99	47	146	50
		max	27	30	21	77	61			19	139	
1964-83c	1330	8	32	34	33	68	47	85	58	33	10	32
		max	27	31	29	67	45			31	93	
OGO 2	19,493	8	39	28	30	52	57	98	66	94	110	39
		max	28	11	7	47	49			94	108	
OGO 4	13,156	8	61	39	40	85	89	126	89	114	144	57
		max	51	15	9	82	80			114	142	
Max. value of n^*			10	9	11	10	10	8	8	9	12	8

Table 5—Deviations from IGRF(10/68).

g n	m	GSFC(12/66)	AFCRL(3/68)	RGO-2	IZMIRAN	USCGS	RGO-1	IGRF
1	0	6	0	-11	-20	0	6	-30339
1	1	5	-10	8	-25	11	-15	-2123
2	0	-6	-3	14	24	-7	-3	-1654
2	1	3	-1	-15	6	5	-2	2994
2	2	-6	12	18	-15	28	6	1567
3	0	3	5	-18	1	5	10	1297
3	1	-6	-3	28	2	-6	1	-2036
3	2	0	1	0	0	10	5	1289
3	3	5	13	19	-85	14	24	843
4	0	-1	7	-18	18	-2	-4	958
4	1	2	1	-13	9	-2	7	805
4	2	2	2	-8	-7	-15	-1	492
4	3	-2	1	3	4	11	8	-392
4	4	-7	14	3	10	-1	20	256
5	0	-2	3	16	-19	0	-7	-223
5	1	2	-6	10	-13	3	-4	357
5	2	1	-7	-7	17	1	-4	246
5	3	-3	0	-2	21	-7	-2	-26
5	4	0	10	-5	-13	-7	17	-161
5	5	-1	7	-13	9	-3	-2	-51
6	0	0	-1	-8	15	-1	-1	47
6	1	2	-5	-5	8	1	-1	60
6	2	-1	2	-2	2	6	3	4
6	3	3	-8	-4	3	-4	-15	-229
6	4	0	-2	4	-1	0	-9	3
6	5	3	-8	7	-16	-7	3	-4
6	6	5	9	0	-48	-32	20	-112
7	0	-2	4	6	-7	1	5	71
7	1	-2	1	7	-1	1	2	-54
7	2	0	-3	2	4	4	-2	0
7	3	-1	8	0	-9	2	7	12
7	4	1	-2	-3	6	2	-7	-25
7	5	1	-2	-3	1	3	-11	-9
7	6	2	-7	2	0	-1	-3	13
7	7	3	-10	7	-8	-7	-5	-2
8	0	0	-1	-4	6	0	4	10
8	1	0	-4	4	1	-6	-2	9
8	2	3	-2	-3	-6	-2	-2	-3
8	3	2	-2	-5	2	2	-4	-12
8	4	0	-4	6	-2	-1	2	-4
8	5	-2	-3	3	11	7	-4	7
8	6	-1	-2	0	13	9	1	-5
8	7	0	-3	0	4	3	-10	12
8	8	-1	2	0	2	3	-6	6

TABLE 5(a)

and others (Cain et al., 1965; Cain et al., 1967; Cain and Hendricks, 1968), ambient values of the earth's field depend on contributions from the core, crust, subsurface, and ionospheric electric currents; and from the effects of trapped plasma, magnetospheric boundary, and tail effects. The precise secular variation is subject to shifts which make a linear fit with time increasingly uncertain beyond a few years. Further, even for the decade of validity of the IGRF, 1960-1969, we know that there are more accurate models available.

n	$\overset{h}{m}$	GSFC(12/66)	AFCRL(3/68)	RGO-2	IZMIRAN	USCGS	RGO-1	IGRF
1	0	0	0	0	0	0	0	0
1	1	0	16	12	-52	11	32	5758
2	0	0	0	0	0	0	0	0
2	1	4	-11	6	-9	-6	4	-2006
2	2	-11	10	-15	71	-7	12	130
3	0	0	0	0	0	0	0	0
3	1	6	-6	-22	12	-3	-2	-403
3	2	-2	-3	-1	22	-3	7	242
3	3	10	-19	20	-53	16	-8	-176
4	0	0	0	0	0	0	0	0
4	1	1	-6	12	-10	4	-10	149
4	2	6	-6	0	-28	5	-8	-280
4	3	3	-7	3	-9	7	-2	8
4	4	-16	-4	11	90	35	-7	-265
5	0	0	0	0	0	0	0	0
5	1	-1	11	2	-22	4	1	16
5	2	1	3	8	-23	1	-5	125
5	3	-5	5	1	23	-4	-7	-123
5	4	1	-10	10	1	9	-3	-107
5	5	4	3	-2	-25	-2	-7	77
6	0	0	0	0	0	0	0	0
6	1	2	-2	-3	-4	3	9	-14
6	2	-1	-1	1	6	1	3	106
6	3	1	0	-10	8	0	0	68
6	4	2	6	1	-26	-12	-2	-32
6	5	-2	3	-6	15	13	-4	-10
6	6	3	-4	3	-17	-12	-4	-13
7	0	0	0	0	0	0	0	0
7	1	-2	5	11	-16	-6	0	-57
7	2	0	-3	2	0	1	2	-27
7	3	2	-2	-2	-6	-1	-8	-8
7	4	2	-5	-1	3	-2	-4	9
7	5	-1	-3	1	8	1	-3	23
7	6	-1	3	-3	3	0	-5	-19
7	7	0	1	-4	4	-2	-5	-17
8	0	0	0	0	0	0	0	0
8	1	-1	7	-7	1	7	6	3
8	2	0	-1	6	-9	0	7	-13
8	3	-1	7	-4	-3	2	13	5
8	4	-2	3	1	6	5	-4	-17
8	5	1	-2	1	-6	-5	1	4
8	6	0	-3	2	4	4	-7	22
8	7	0	-1	7	-7	-7	-4	-3
8	8	-3	3	1	8	6	-9	-16

TABLE 5(b)

The IGRF was developed to fill the need for a standard field model in which the permanence of a standard over a period of years outweighs the advantages of a high accuracy. Thus, the ultimate use of this model and further requests for revisions must be left to the users.

The way to test the applicability of IGRF(10/68) to a particular problem is to perform regular tests of newer or more accurate models and compare the results with those based on IGRF. As the core field deviates more and more from the IGRF estimate, the accuracy will continuously decrease.

n	$\dot{g}$ m	GSFC(12/66)	AFCRL(3/68)	RGO-2	IZMIRAN	USCGS	RGO-1	IGRF
1	0	-1.5	-3.3	1.7	3.3	-0.3	0.2	15.3
1	1	0.7	-1.9	0.3	-1.0	1.8	-0.4	8.7
2	0	0.3	-3.3	0.4	-0.7	3.3	-2.2	-24.4
2	1	-0.5	-0.5	-1.3	-0.2	2.4	-1.6	0.3
2	2	-4.2	-2.0	3.6	0.4	2.1	2.9	-1.6
3	0	-1.7	0.1	-0.2	0.6	1.1	-0.2	0.2
3	1	0.0	0.6	0.8	1.9	-3.3	1.3	-10.8
3	2	1.7	0.5	-1.7	-0.7	0.2	-2.6	0.7
3	3	-3.1	-3.0	2.8	2.1	1.3	3.2	-3.8
4	0	2.1	1.4	-0.3	0.9	-4.1	1.3	-0.7
4	1	0.5	0.6	-0.2	0.1	-1.0	0.8	0.2
4	2	1.3	2.6	-1.0	0.7	-3.6	0.8	-3.0
4	3	0.8	-0.4	1.1	0.1	-1.7	0.3	-0.1
4	4	-1.4	1.2	-0.9	0.8	0.3	-0.9	-2.1
5	0	-0.0	1.4	-0.9	-1.3	0.7	-1.1	1.9
5	1	-0.5	-0.5	-1.1	-0.8	2.9	-0.7	1.1
5	2	0.9	-0.2	0.1	-1.8	0.9	-1.3	2.9
5	3	-0.6	-0.2	-1.6	-1.0	3.2	-0.9	0.6
5	4	-0.6	1.5	-1.0	-0.7	0.8	-1.1	0.0
5	5	0.8	2.7	-0.3	-1.2	-2.1	0.4	1.3
6	0	-0.4	-1.1	0.1	-0.4	1.8	0.1	-0.1
6	1	1.2	-0.7	0.3	0.6	-1.3	-0.2	-0.3
6	2	-0.2	-0.6	-0.1	-0.4	1.2	0.7	1.1
6	3	0.7	-0.7	0.1	-0.6	0.4	-0.5	1.9
6	4	1.2	0.9	0.4	0.8	-3.4	1.0	-0.4
6	5	0.6	-2.3	0.4	0.4	0.9	0.6	-0.4
6	6	0.6	0.6	-0.8	0.2	-0.6	-2.0	-0.2
7	0	-0.1	0.7	0.5	0.5	-1.6	0.5	-0.5
7	1	-0.0	-0.0	0.3	0.3	-0.6	0.3	-0.3
7	2	-0.9	-0.3	0.7	0.7	-0.2	0.7	-0.7
7	3	-0.4	1.3	0.5	0.5	-1.9	0.5	-0.5
7	4	-0.3	-0.8	-0.3	-0.3	1.5	-0.3	0.3
7	5	-0.7	-0.7	0.0	0.0	1.4	0.0	-0.0
7	6	0.0	0.9	0.2	0.2	-1.3	0.2	-0.2
7	7	-0.1	-1.6	0.6	0.6	0.5	0.6	-0.6
8	0	0.3	-0.3	-0.1	-0.1	0.3	-0.1	0.1
8	1	0.1	-0.1	-0.4	-0.4	0.8	-0.4	0.4
8	2	1.3	-0.5	-0.6	-0.6	0.3	-0.6	0.6
8	3	-0.2	-0.8	-0.0	-0.0	1.1	-0.0	0.0
8	4	0.5	-0.8	0.0	0.0	0.2	0.0	-0.0
8	5	-0.0	-0.1	0.1	0.1	-0.0	0.1	-0.1
8	6	0.2	-0.7	-0.3	-0.3	1.1	-0.3	0.3
8	7	0.1	-1.4	0.3	0.3	0.6	0.3	-0.3
8	8	0.0	-0.4	0.5	0.5	-0.6	0.5	-0.5

TABLE 5(c)

We have already made this test for the application to analysis of the time variations of the Cosmos 49, OGO 2, and OGO 4 data. For such studies the IGRF is not useful, the GSFC(12/66) model is insufficient, and fits based on the data themselves are being used. For higher accuracy studies, we suggest using the GSFC(12/66) model over the range 1900-1965 and the POGO(10/68) model for 1965-1968. Beyond 1968, POGO(10/68) can be used until it is updated by more recent data and planned improvements in the analysis.

$\dot{h}$

n	m	GSFC(12/66)	AFCRL(3/68)	RGO-2	IZMIRAN	USCGS	RGO-1	IGRF
1	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	1	-1.7	1.4	2.3	-0.2	-1.7	2.9	-2.3
2	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	1	-2.3	-4.1	-0.2	2.0	4.7	0.4	-11.8
2	2	0.0	1.3	-1.3	0.9	-1.1	-1.5	-16.7
3	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	1	1.5	0.8	0.8	0.1	-3.1	-1.0	4.2
3	2	1.8	1.4	0.3	0.0	-3.7	0.9	0.7
3	3	1.1	-3.3	-1.3	2.1	1.5	-0.8	-7.7
4	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	1	-2.1	-1.4	1.1	1.5	1.0	3.1	-0.1
4	2	-1.4	-3.0	-0.6	-0.7	5.7	-2.3	1.6
4	3	-1.2	-0.2	0.1	-0.4	1.7	-0.2	2.9
4	4	-2.6	-0.3	1.2	2.6	-0.8	1.5	-4.2
5	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	1	-0.3	-0.1	-0.3	-1.9	2.6	-0.4	2.3
5	2	-0.1	0.5	0.3	-0.3	-0.3	0.6	1.7
5	3	-0.3	0.6	0.4	1.2	-1.9	0.6	-2.4
5	4	-0.3	-2.6	0.2	-0.6	3.4	0.6	0.8
5	5	0.1	0.2	0.3	0.5	-1.1	0.8	-0.3
6	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	1	1.1	0.5	-1.1	0.5	-1.0	-1.3	-0.9
6	2	0.4	0.5	1.4	0.6	-2.9	0.6	-0.4
6	3	0.6	-0.1	-0.0	-1.1	0.8	-1.1	2.0
6	4	-0.3	1.3	0.1	1.1	-2.1	-1.0	-1.1
6	5	0.4	0.5	-0.1	-0.1	-0.7	-0.2	0.1
6	6	-0.1	-1.3	0.1	-0.9	2.3	-1.1	0.9
7	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	1	0.1	0.5	1.1	1.1	-2.7	1.1	-1.1
7	2	-0.2	-1.1	-0.3	-0.3	1.9	-0.3	0.3
7	3	0.1	0.5	-0.4	-0.4	0.2	-0.4	0.4
7	4	0.6	-0.6	-0.2	-0.2	0.4	-0.2	0.2
7	5	-0.8	-0.8	-0.4	-0.4	2.4	-0.4	0.4
7	6	0.4	1.5	-0.2	-0.2	-1.4	-0.2	0.2
7	7	0.7	1.1	-0.3	-0.3	-1.2	-0.3	0.3
8	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8	1	-0.7	-0.4	-0.1	-0.1	1.3	-0.1	0.1
8	2	-0.1	-0.0	0.2	0.2	-0.2	0.2	-0.2
8	3	0.4	-0.7	0.3	0.3	-0.4	0.3	-0.3
8	4	-0.7	-0.2	0.2	0.2	0.5	0.2	-0.2
8	5	0.4	-0.1	0.3	0.3	-1.0	0.3	-0.3
8	6	0.5	0.2	0.4	0.4	-1.5	0.4	-0.4
8	7	-0.1	-1.0	0.3	0.3	0.5	0.3	-0.3
8	8	-0.2	-0.4	0.3	0.3	0.1	0.3	-0.3

TABLE 5(d)

The magnetic field derived from the IGRF or other magnetic field coefficients can be calculated from a wide variety of computer programs currently available. One such set of programs, based on a code originally developed by Jensen and Whitaker (1960), may be obtained from

World Data Center A for Rockets and Satellites
Goddard Space Flight Center (601)
Greenbelt, Maryland 20771

Table 6—Final IGRF(10/68) coefficients.

		EPOCH = 1965.0		I.G.R.F.(10/68)	
n	m	g	h	$\dot{g}$	$\dot{h}$
1	0	-30339	0	15.3	0.0
1	1	-2123	5758	8.7	-2.3
2	0	-1654	0	-24.4	0.0
2	1	2994	-2006	0.3	-11.8
2	2	1567	130	-1.6	-16.7
3	0	1297	0	0.2	0.0
3	1	-2036	-403	-10.8	4.2
3	2	1289	242	0.7	0.7
3	3	843	-176	-3.8	-7.7
4	0	958	0	-0.7	0.0
4	1	805	149	0.2	-0.1
4	2	492	-280	-3.0	1.6
4	3	-392	8	-0.1	2.9
4	4	256	-265	-2.1	-4.2
5	0	-223	0	1.9	0.0
5	1	357	16	1.1	2.3
5	2	246	125	2.9	1.7
5	3	-26	-123	0.6	-2.4
5	4	-161	-107	0.0	0.8
5	5	-51	77	1.3	-0.3
6	0	47	0	-0.1	0.0
6	1	60	-14	-0.3	-0.9
6	2	4	106	1.1	-0.4
6	3	-229	68	1.9	2.0
6	4	3	-32	-0.4	-1.1
6	5	-4	-10	-0.4	0.1
6	6	-112	-13	-0.2	0.9
7	0	71	0	-0.5	0.0
7	1	-54	-57	-0.3	-1.1
7	2	0	-27	-0.7	0.3
7	3	12	-8	-0.5	0.4
7	4	-25	9	0.3	0.2
7	5	-9	23	-0.0	0.4
7	6	13	-19	-0.2	0.2
7	7	-2	-17	-0.6	0.3
8	0	10	0	0.1	0.0
8	1	9	3	0.4	0.1
8	2	-3	-13	0.6	-0.2
8	3	-12	5	0.0	-0.3
8	4	-4	-17	-0.0	-0.2
8	5	7	4	-0.1	-0.3
8	6	-5	22	0.3	-0.4
8	7	12	-3	-0.3	-0.3
8	8	6	-16	-0.5	-0.3

These programs internally convert the Schmidt-normalized coefficients to a more efficient Gauss-normalized form, update them to the epoch requested, and compute the geocentric components from the scalar gradient of the potential function, given the geocentric position. Conversions are also provided from geodetic position to geocentric, as well as routines for rotating the output geocentric components into geodetic directions. Ignoring the differences between geodetic and geocentric coordinates will create errors up to about 200γ.

Goddard Space Flight Center
National Aeronautics and Space Administration
Greenbelt, Maryland, January 13, 1971
841-12-04-12-51

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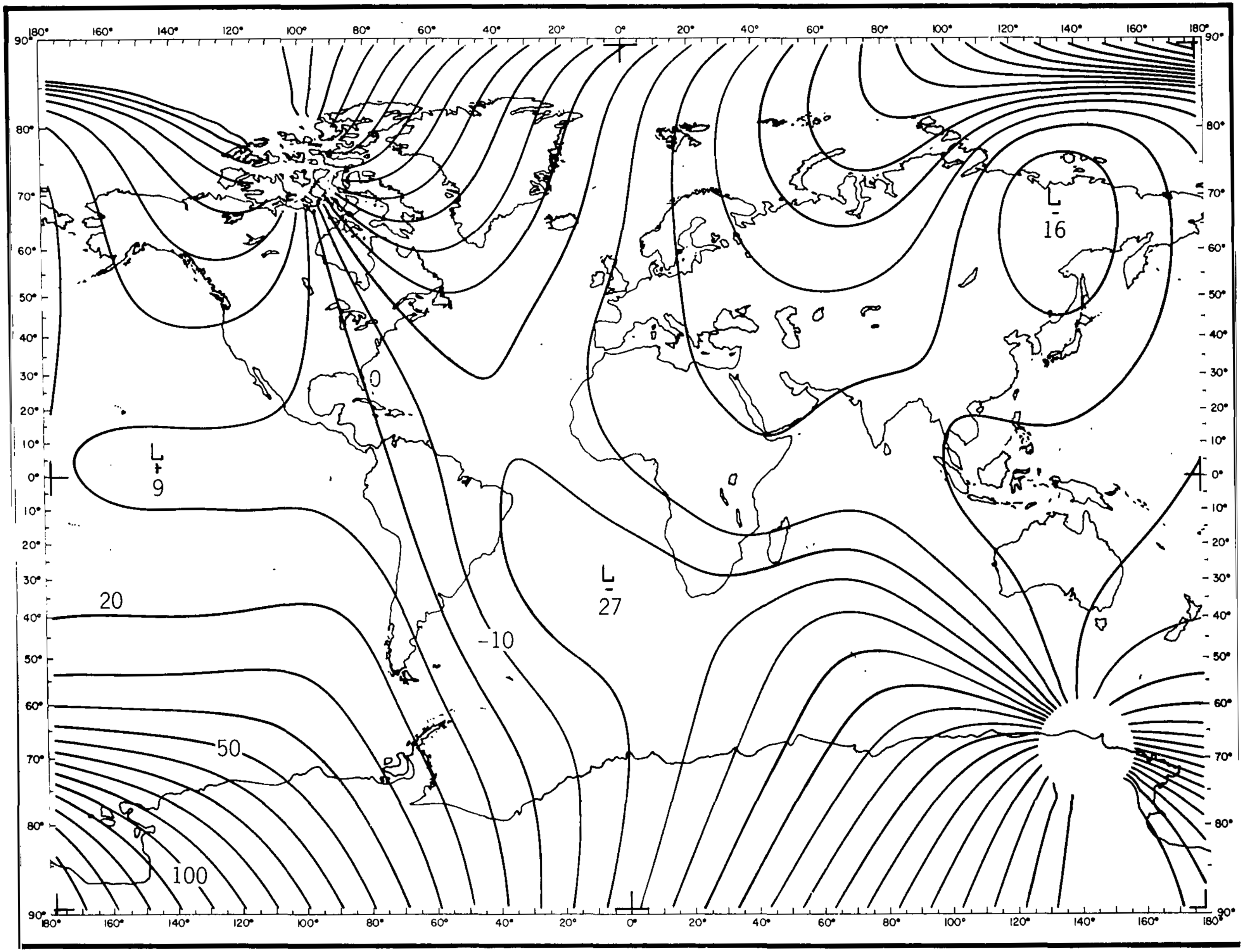
Appendix 1

Main Field Component and Isoporic Charts Computed From IGRF(10/68) for 1965.0 at the Earth's Surface

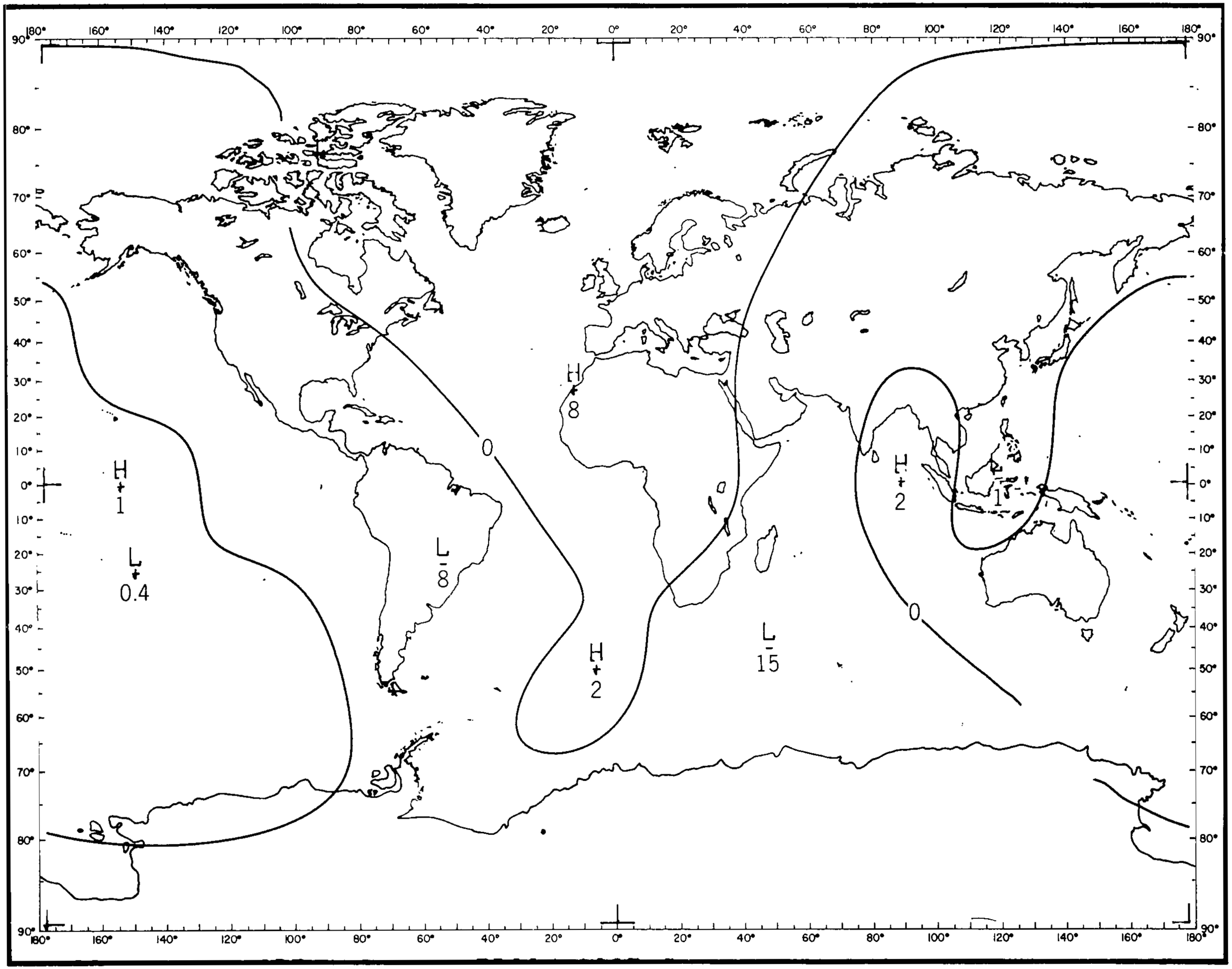
The following figures represent the surface contours of the various geodetic components of the geomagnetic field and its secular change as computed by the IGRF. These diagrams are very similar to those given by Cain and Hendricks (1968) for the GSFC(12/66) field and are drawn automatically using a computer program originally used for weather maps (Cain and Neilon, 1963).

The plots are thus drawn to include the algebraic "lows" and "highs" of the component being displayed. These extrema occur at the center of the "+" or "–" symbols. The dip poles are noted for the H chart as "⊕".

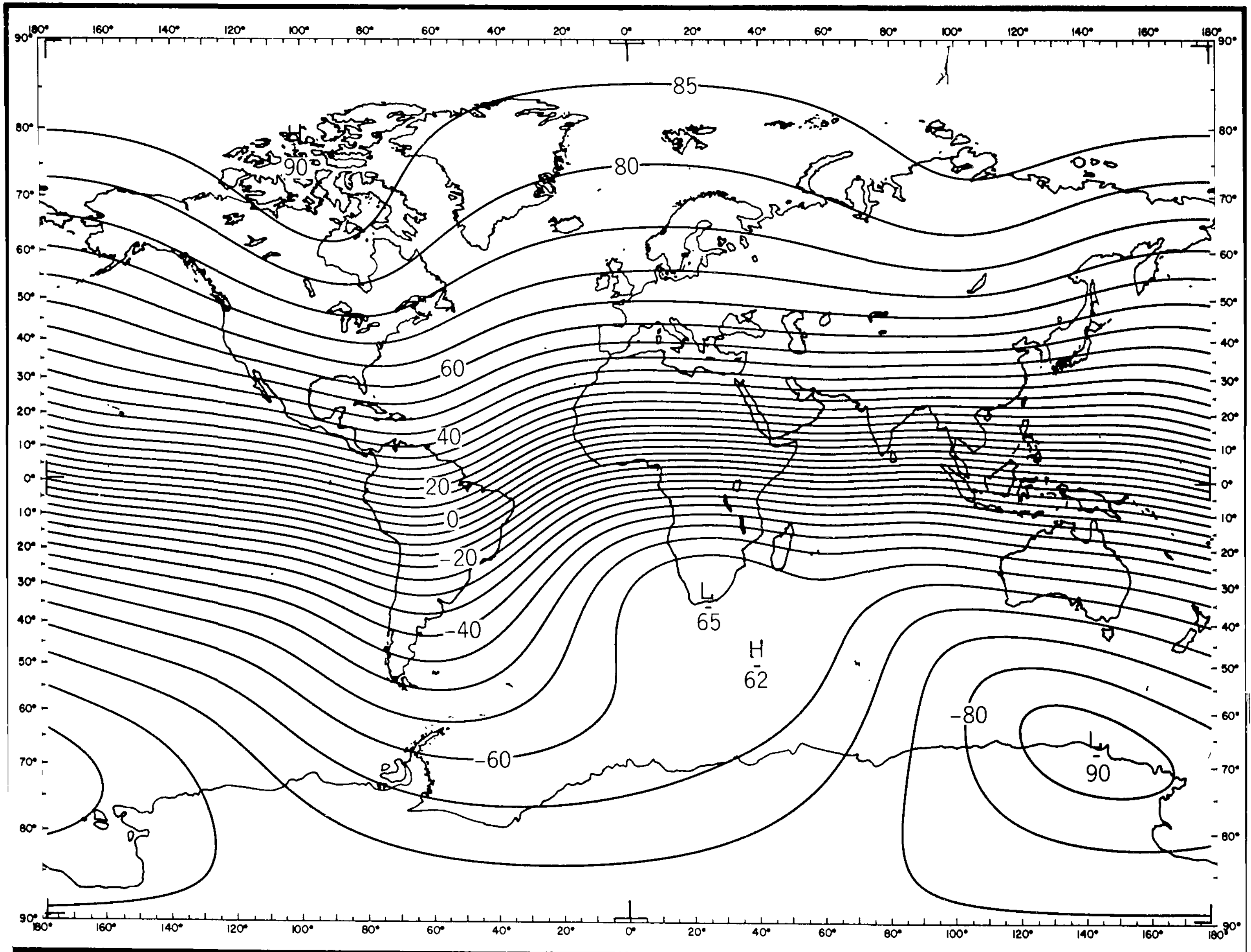
DECLINATION (degrees) D



SECULAR CHANGE OF DECLINATION (minutes/year) $\dot{D}$

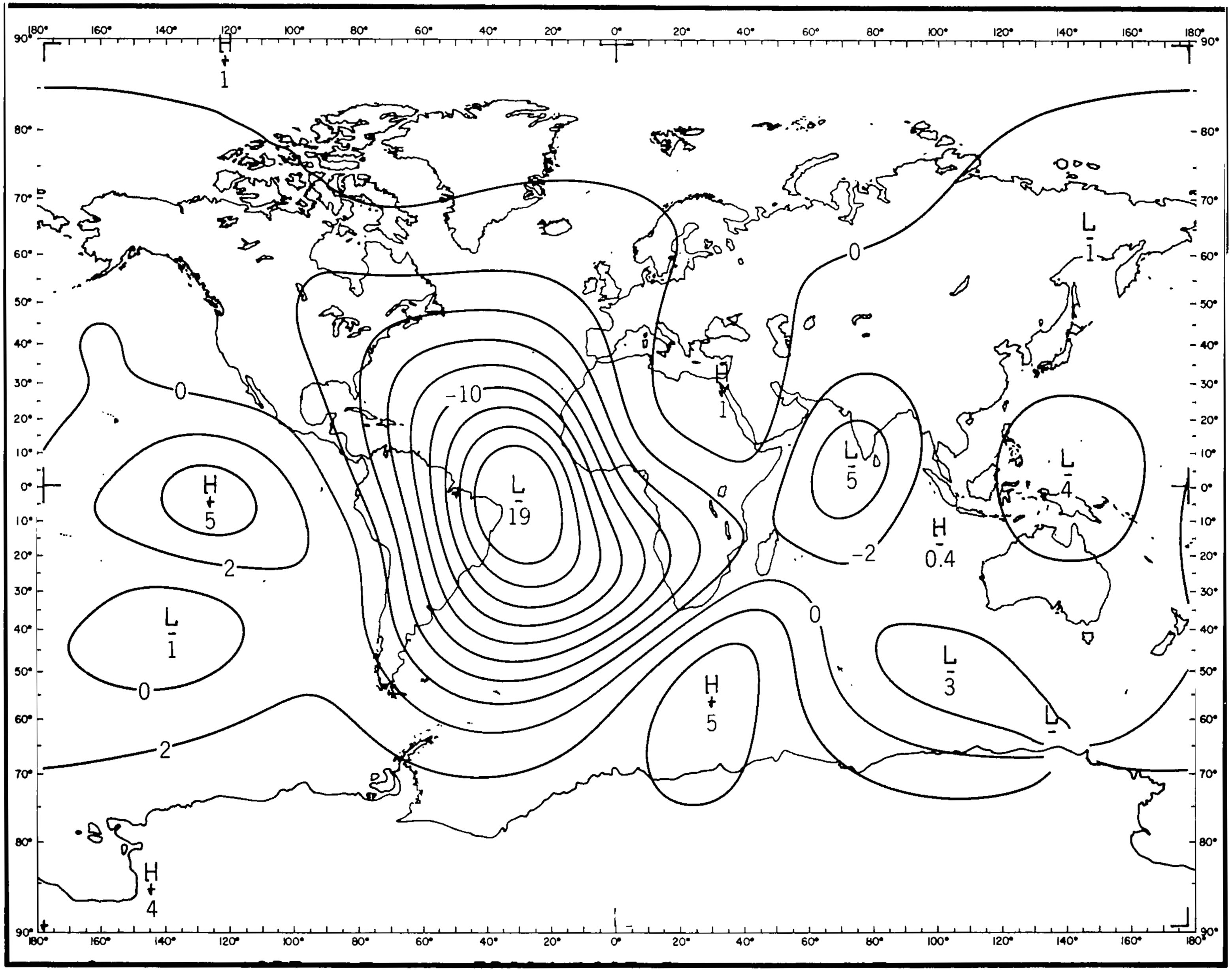


INCLINATION (degrees) I

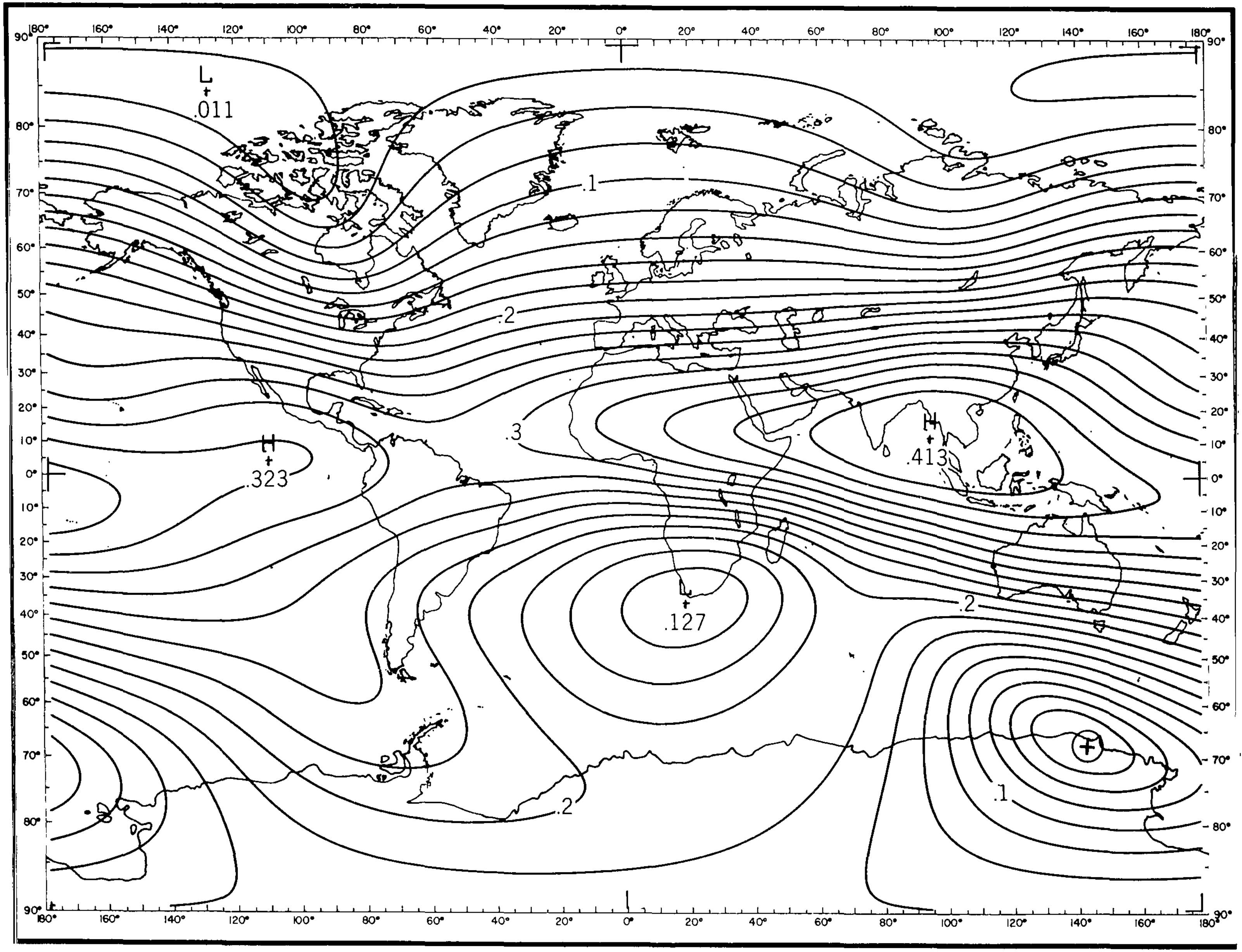


SECULAR CHANGE OF INCLINATION (minutes/year)

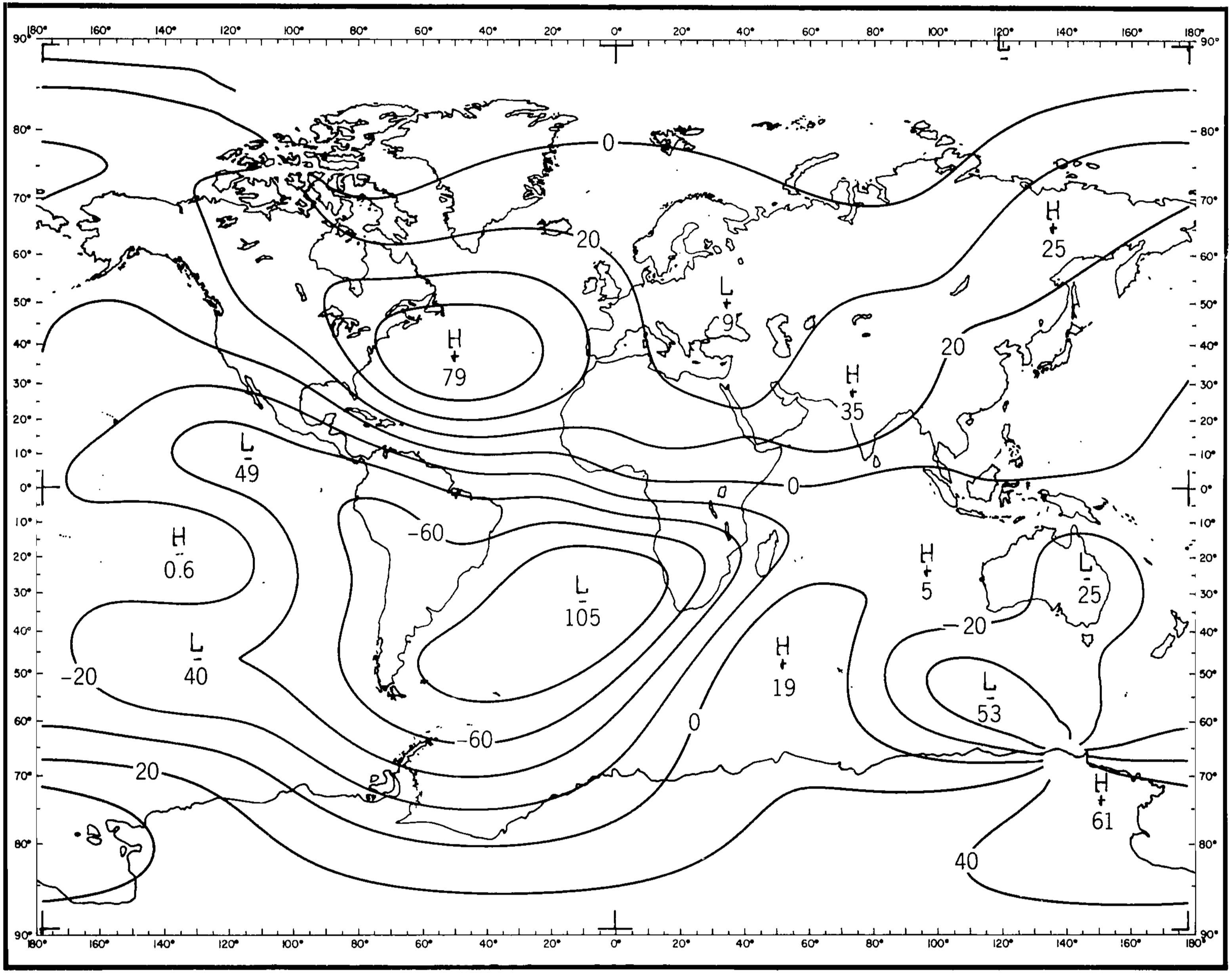
İ



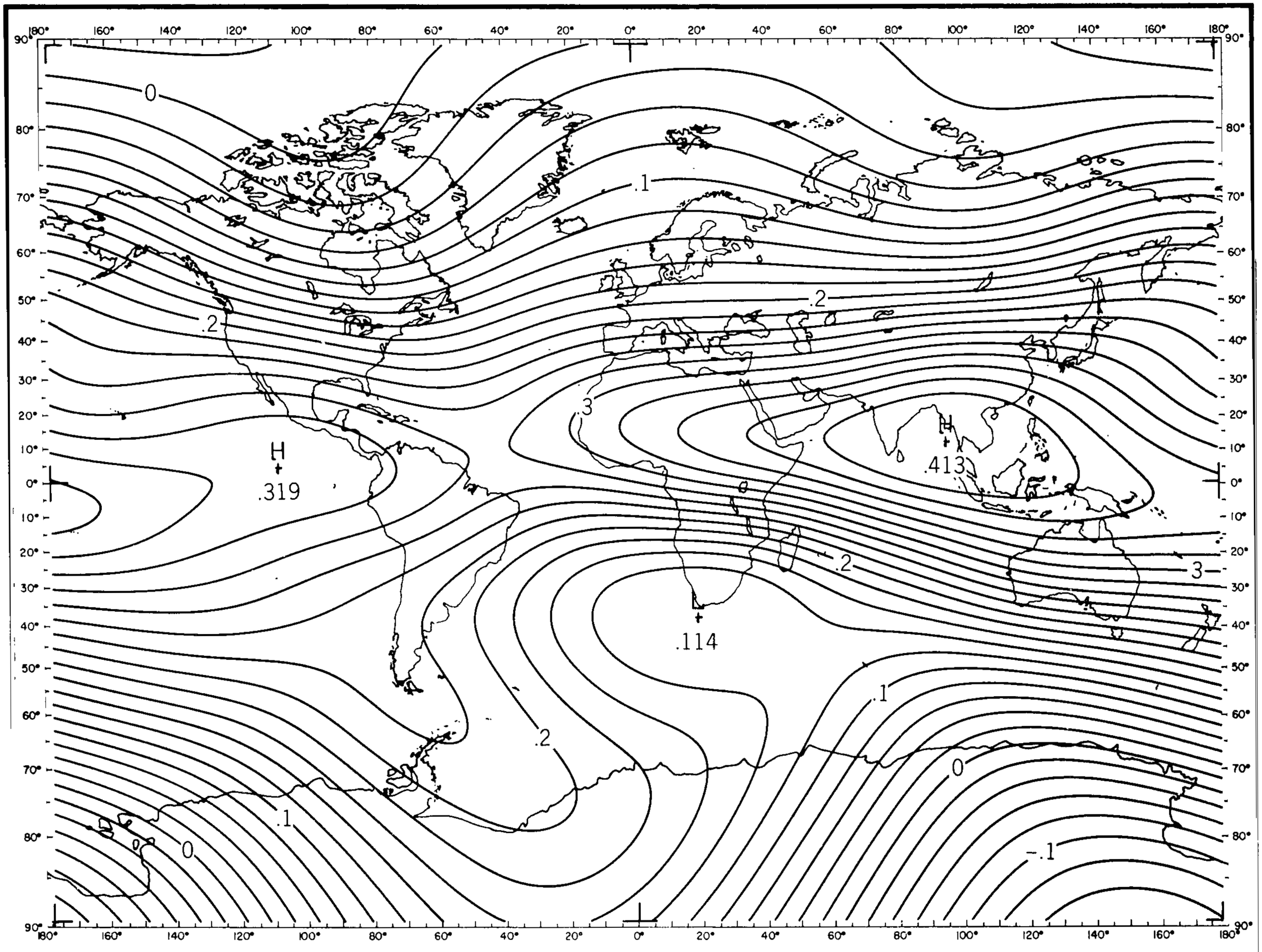
HORIZONTAL FORCE (gauss) H



SECULAR CHANGE OF HORIZONTAL FORCE (gamma/year) $\dot{H}$

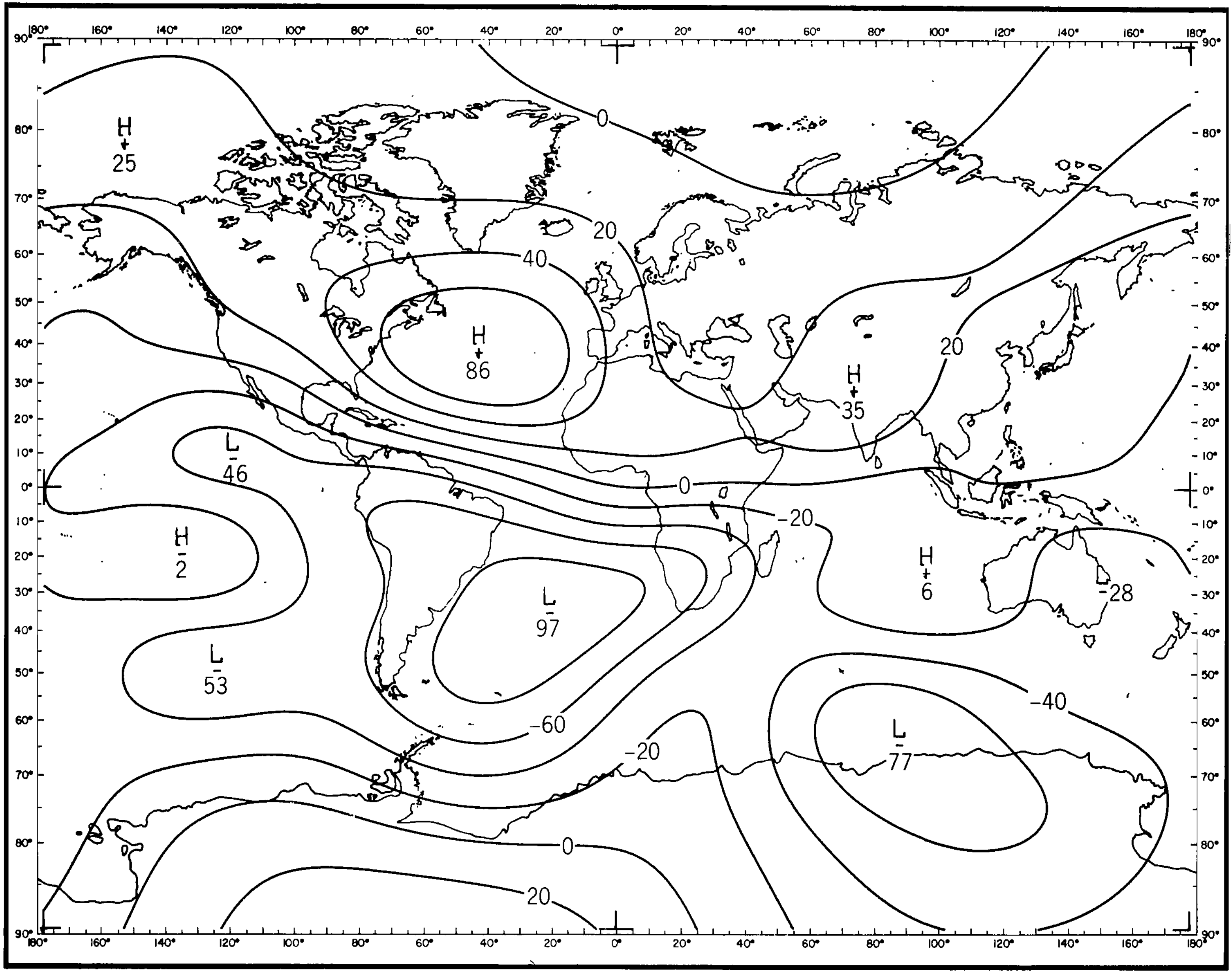


NORTH FORCE (gauss) X

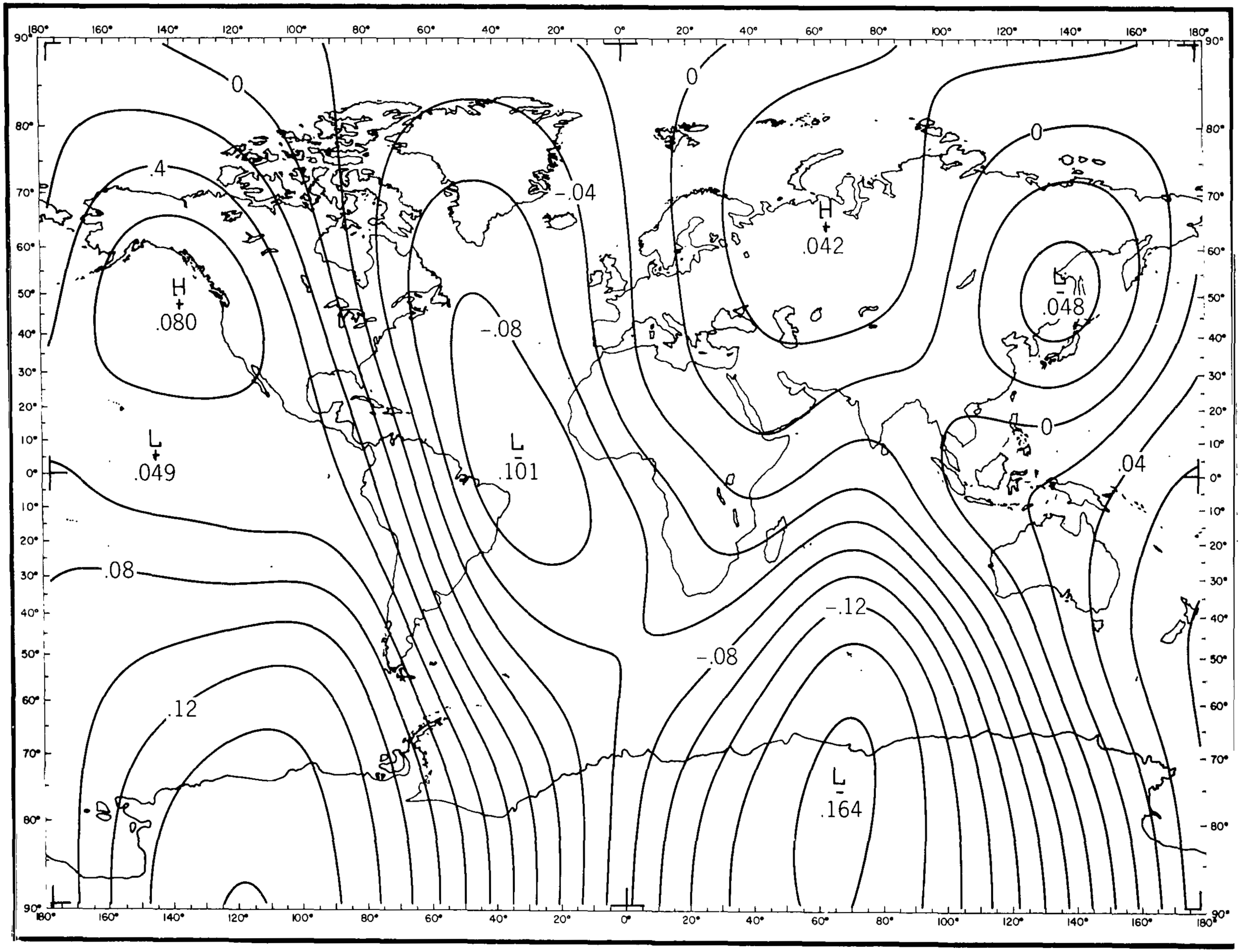


SECULAR CHANGE OF NORTH FORCE (gammas/year)

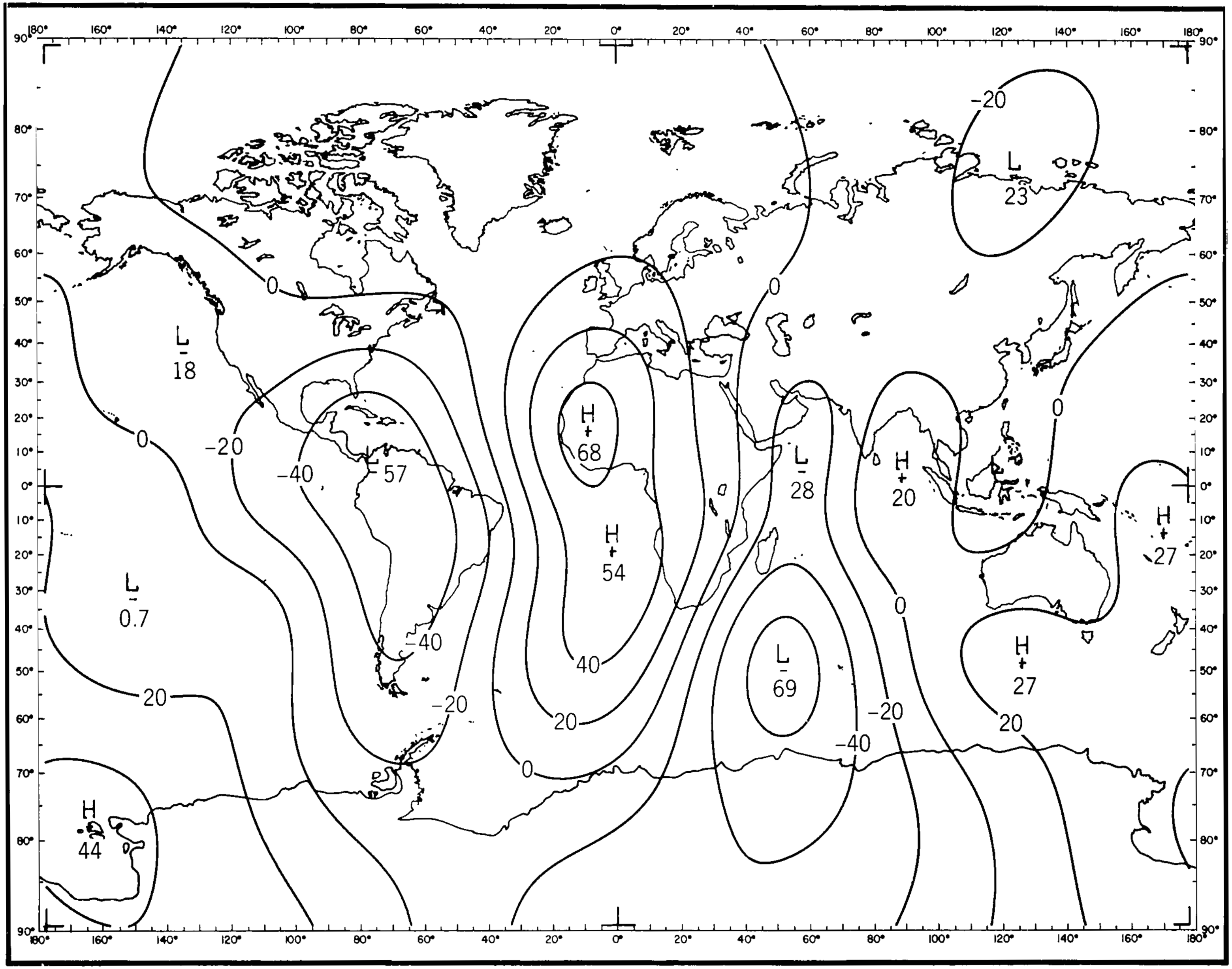
$\dot{X}$



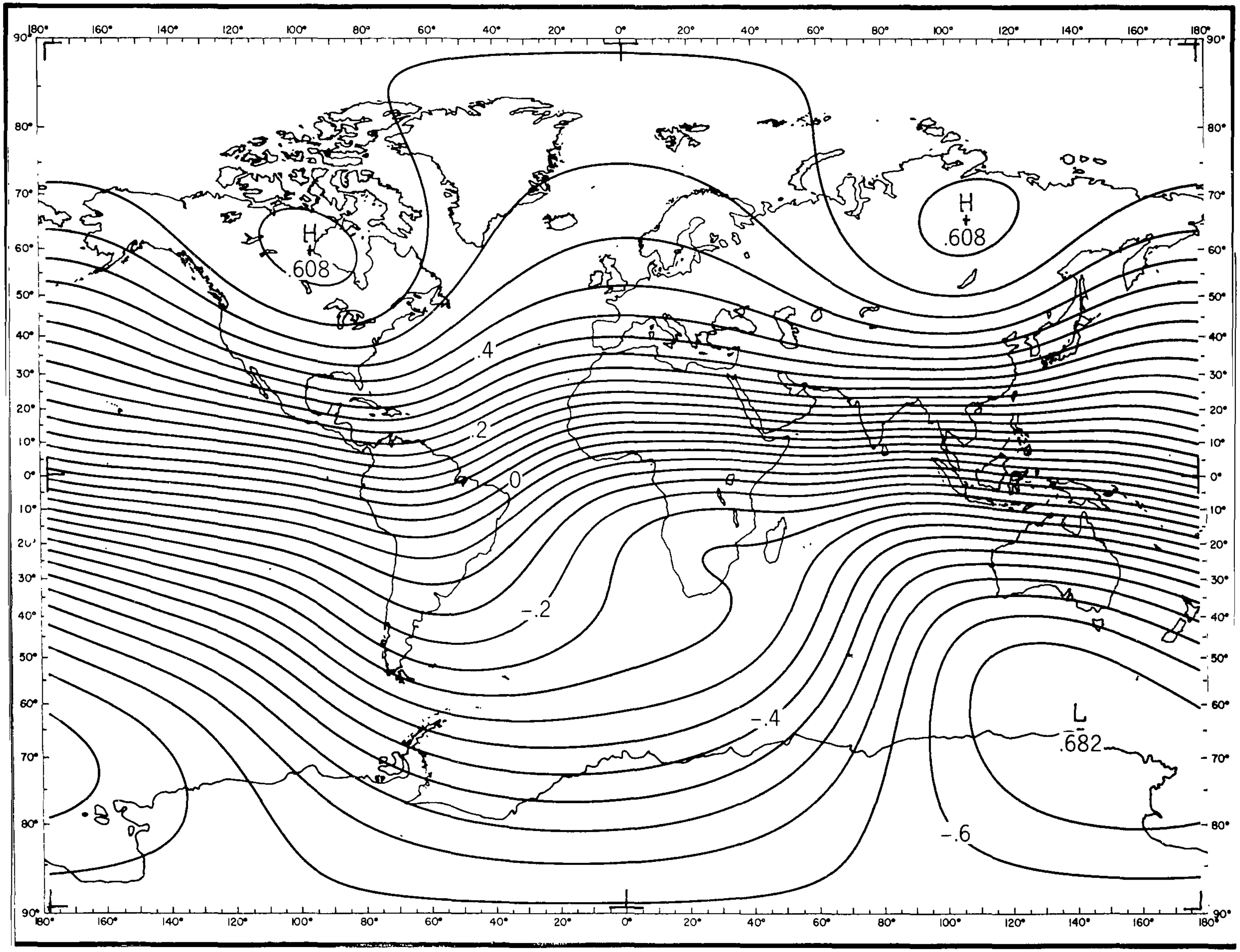
EAST FORCE (gauss) Y



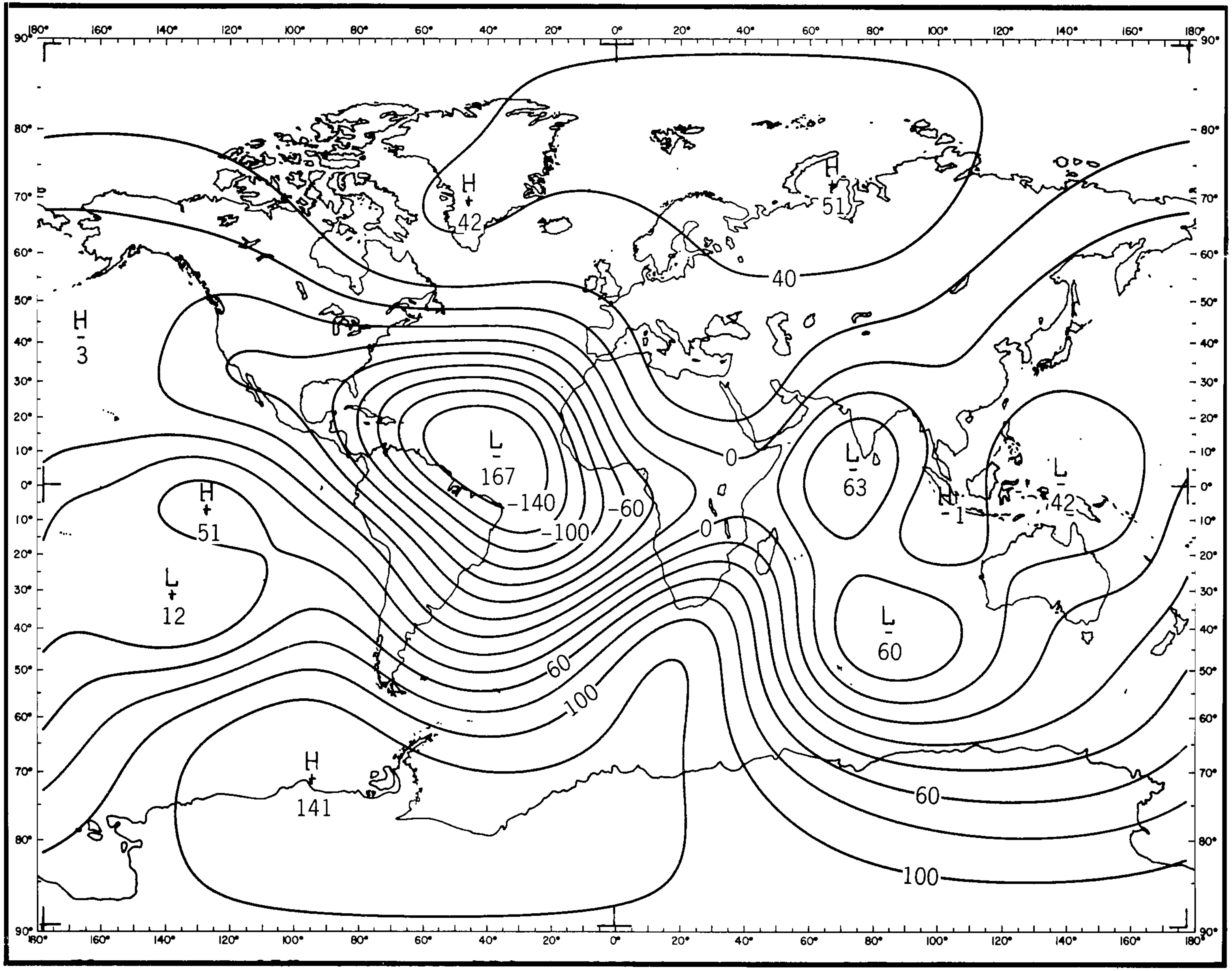
SECULAR CHANGE OF EAST FORCE (gammas/year) $\dot{Y}$



VERTICAL FORCE (gauss) Z

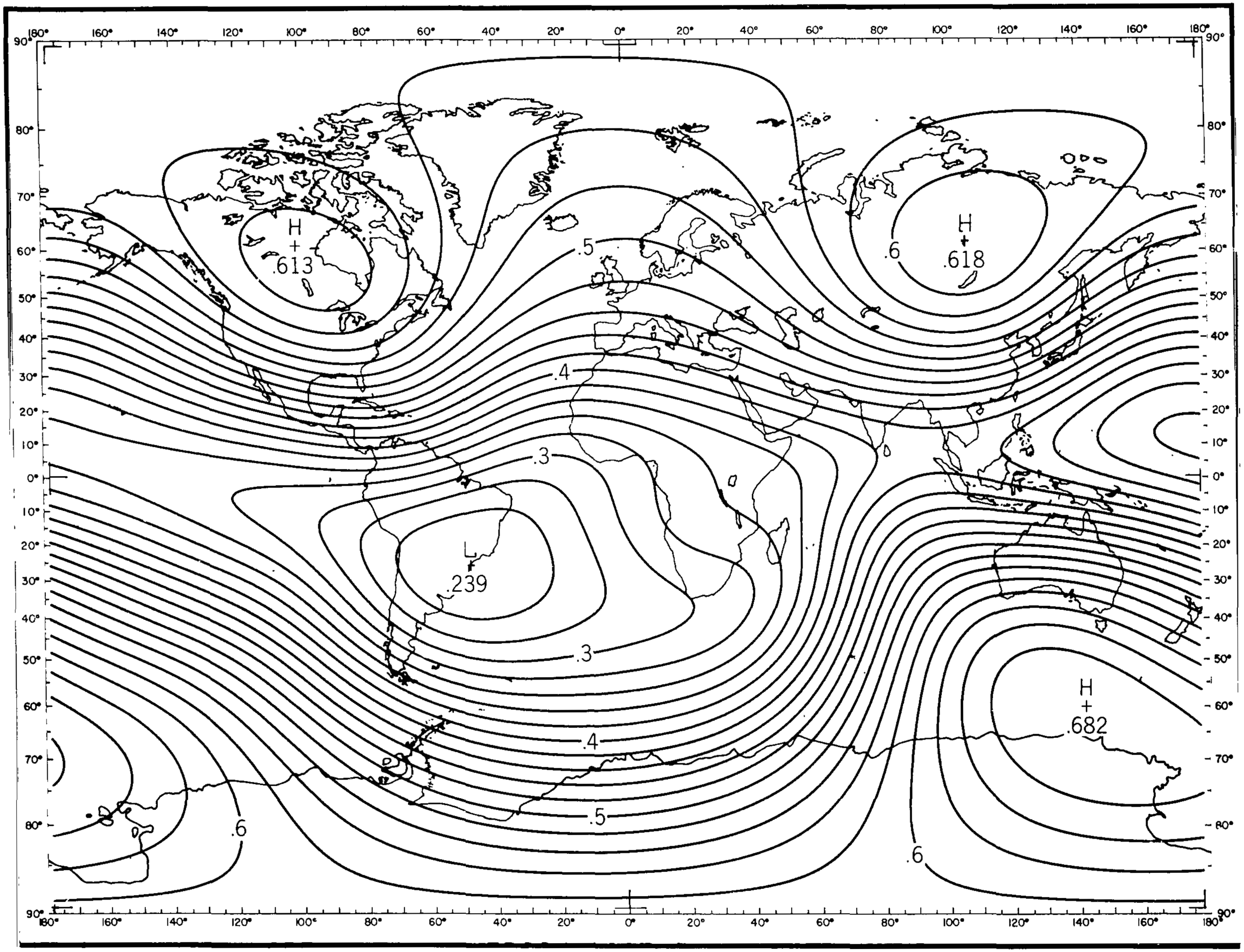


SECULAR CHANGE OF VERTICAL FORCE (gammas/year) $\dot{Z}$



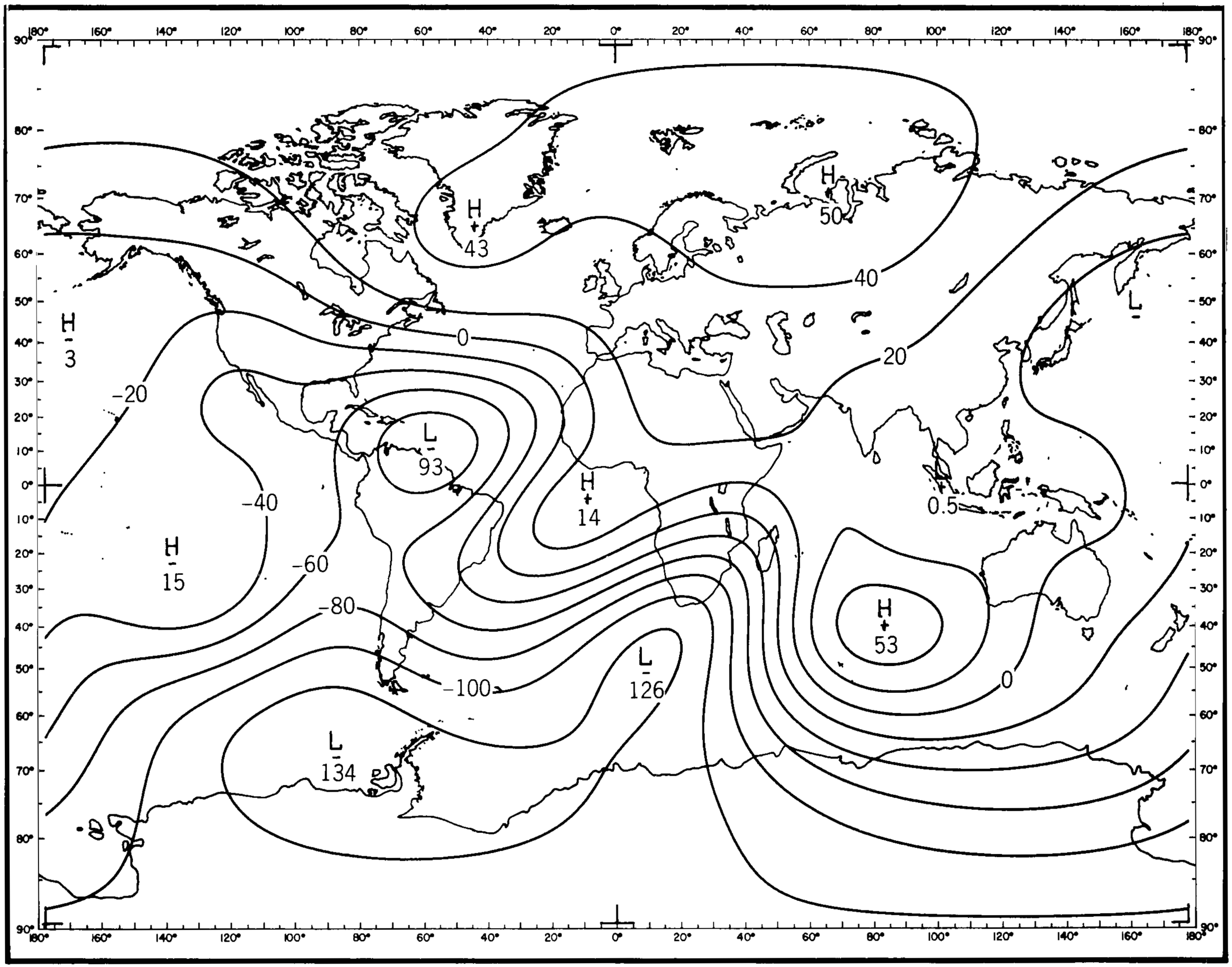
TOTAL FORCE (gauss)

F



SECULAR CHANGE OF TOTAL FORCE (gammas/year)

$\dot{F}$



Appendix 2

Coefficient Normalization

All of the previous field derivations have arbitrarily set the earth's mean radius at 6371.2 for the value of a in the factors $(a/r)^{n+1}$ of the potential expansion. This value stemmed from the old standard earth constants with equatorial radius 6378.388 and flattening 1/297. However, the new constants have become 6378.165 and 1/298.25 respectively. Integrating

$$\bar{r} = \int_0^{\pi/2} r \cos\theta \, d\theta ,$$

we obtain

$$\bar{r} = \frac{a}{m} \ln\left(\frac{m+a}{b}\right) ,$$

where

$$m = \sqrt{\frac{a^2 - b^2}{b}} ,$$

a = equatorial radius,

and

$b = a(1 - f)$ is the polar radius with f the flattening factor.

The values with the old and new constants are as follows.

f	a	b	$\bar{r}$
297	6378.39	6356.91	6371.21
298.25	6378.16	6356.77	6371.02

It is recommended that for the sake of simplicity and not to be restricted to constants of only historical significance, we adopt the value of 6371 for a. This is a very slight change and has only the effect of altering the g_1^0 term from −30,339 to −30,342 and the h_1^1 term from 5758 to 5759. The constants α used to make the correction $g = g' + \alpha g'$, where g' is the old value of g or h, are

n	1	2	3	4	5	6	7	8	9	10	11	12
$\alpha \times 10^5$	9	13	16	19	22	25	28	31	35	38	41	44

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